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Appendix F

Human Health Impacts Primer and Details for Estimating Health Impacts to Workers from Yucca Mountain Repository Operations

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APPENDIX F. HUMAN HEALTH IMPACTS PRIMER AND DETAILS FOR ESTIMATING HEALTH IMPACTS TO WORKERS FROM YUCCA MOUNTAIN REPOSITORY OPERATIONS

Section F.1 of this appendix contains information that supports the estimates of human health and safety impacts in this environmental impact statement (EIS). Specifically, Section F.1 is a primer that explains the natures of radiation and toxic materials, where radiation comes from in the context of the radiological impacts discussed in this EIS, how radiation interacts with the human body to produce health impacts, and how toxic materials interact with the body to produce health impacts. The remainder of the appendix discusses the methodology that was used to estimate worker health impacts and the input data to the analysis, and presents the detailed results of the analysis of worker health impacts.

Section F.2 discusses the methodology and data that the U.S. Department of Energy (DOE) used to estimate worker health and safety impacts for the Proposed Action. It also discusses the detailed results of the impact analysis.

Section F.3 discusses the methodologies and data that DOE used to estimate worker health and safety impacts for Inventory Modules 1 and 2. It also discusses the detailed results of the impact analysis.

Section F.4 discusses the methodology and data that DOE used to estimate worker health and safety impacts for retrieval, should such action become necessary. In addition, it discusses the detailed results from the impact analysis.

Radiological impacts to the public from operations at the Yucca Mountain site could result from release of naturally occurring radon-222 and its decay products in the ventilation exhaust from the subsurface repository operations. The methodology and input data used in the estimates of radiological dose to the public are presented in Appendix G, Air Quality. Outside of the radiation primer, health impacts to the public are not treated in this appendix.

F.1 Human Health Impacts from Exposure to Radioactive and Toxic Materials

This section introduces the concepts of human health impacts as a result of exposure to radiation and potentially toxic materials.

F.1.1 RADIATION AND HUMAN HEALTH

F.1.1.1 Radiation

Radiation is the emission and propagation of energy through space or through a material in the form of waves or bundles of energy called photons, or in the form of high-energy subatomic particles. Radiation generally results from atomic or subatomic processes that occur naturally. The most common kind of radiation is *electromagnetic radiation,*

RADIATION

Radiation occurs on Earth in many forms, either naturally or as the result of human activities. Natural forms include light, heat from the sun, and the decay of unstable radioactive elements in the Earth and the environment. Some elements that exist naturally in the human body are radioactive and emit ionizing radiation. They include an isotope of potassium that is an essential element for health and the elements of the uranium and thorium naturally occurring decay series. Human activities have also led to sources of ionizing radiation for various uses, such as diagnostic and therapeutic medicine and nondestructive testing of pipes and welds. Nuclear power generation produces ionizing radiation as well as radioactive materials, which undergo radioactive decay and can continue to emit ionizing radiation for long periods of time.

which is transmitted as photons. Electromagnetic radiation is emitted over a range of wavelengths and energies. We are most commonly aware of visible light, which is part of the spectrum of electromagnetic radiation. Radiation of longer wavelengths and lower energy includes infrared radiation, which heats material when the material and the radiation interact, and radio waves. Electromagnetic radiation of shorter wavelengths and higher energy (which are more penetrating) includes ultraviolet radiation, which causes sunburn, X-rays, and gamma radiation.

Ionizing radiation is radiation that has sufficient energy to displace electrons from atoms or molecules to create ions. It can be electromagnetic (for example, X-rays or gamma radiation) or subatomic particles (for example, alpha and beta radiation). The ions have the ability to interact with other atoms or molecules; in biological systems, this interaction can cause damage in the tissue or organism.

F.1.1.2 Radioactivity, Ionizing Radiation, Radioactive Decay, and Fission

Radioactivity is the property or characteristic of an unstable atom to undergo spontaneous transformation (to *disintegrate* or *decay*) with the emission of energy as radiation. Usually the emitted radiation is ionizing radiation. The result of the process, called *radioactive decay*, is the transformation of an unstable atom (a *radionuclide*) into a different atom, accompanied by the release of energy (as radiation) as the atom reaches a more stable, lower energy configuration.

Radioactive decay produces three main types of ionizing radiation—alpha particles, beta particles, and gamma or X-rays—but our senses cannot detect them. These types of ionizing radiation can have different characteristics and levels of energy and, thus, varying abilities to penetrate and interact with atoms in the human body. Because each type has different characteristics, each requires different amounts of material to stop (shield) the radiation. Alpha particles are the least penetrating and can be stopped by a thin layer of material such as a single sheet of paper. However, if radioactive atoms (called radionuclides) emit alpha particles in the body when they decay, there is a concentrated deposition of energy near the point where the radioactive decay occurs. Shielding for beta particles requires thicker layers of material such as several reams of paper or several inches of wood or water. Shielding from gamma rays, which are highly penetrating, requires very thick material such as several inches to several feet of heavy material (for example, concrete or lead). Deposition of the energy by gamma rays is dispersed across the body in contrast to the local energy deposition by an alpha particle. In fact, some gamma radiation will pass through the body without interacting with it.

FISSION

Fission is the process whereby a large nucleus (for example, uranium-235) absorbs a neutron, becomes unstable, and splits into two fragments, resulting in the release of large amounts of energy per unit of mass. Each fission releases an average of two or three neutrons that can go on to produce fissions in nearby nuclei. If one or more of the released neutrons on the average causes additional fissions, the process keeps repeating. The result is a self-sustaining chain reaction and a condition called criticality. When the energy released in fission is controlled (as in a nuclear reactor), it can be used for various benefits such as to propel submarines or to provide electricity that can light and heat homes.

In a nuclear reactor, heavy atoms such as uranium and plutonium can undergo another process, called *fission*, after the absorption of a subatomic particle (usually a neutron). In fission, a heavy atom splits into two lighter atoms and releases energy in the form of radiation and the kinetic energy of the two new lighter atoms. The new lighter atoms are called fission products. The fission products are usually unstable and undergo radioactive decay to reach a more stable state.

Some of the heavy atoms might not fission after absorbing a subatomic particle. Rather, a new nucleus is formed that tends to be unstable (like fission products) and undergo radioactive decay.

The radioactive decay of fission products and unstable heavy atoms is the source of the radiation from spent nuclear fuel and high-level radioactive waste that makes these materials hazardous in terms of potential human health impacts.

F.1.1.3 Exposure to Radiation and Radiation Dose

Radiation that originates outside an individual's body is called *external* or *direct radiation*. Such radiation can come from an X-ray machine or from *radioactive materials* (materials or substances that contain radionuclides), such as radioactive waste or radionuclides in soil. *Internal radiation* originates inside a person's body following intake of radioactive material or radionuclides through ingestion or inhalation. Once in the body, the fate of a radioactive material is determined by its chemical behavior and how it is metabolized. If the material is soluble, it might be dissolved in bodily fluids and be transported to and deposited in various body organs; if it is insoluble, it might move rapidly through the gastrointestinal tract or be deposited in the lungs.

Exposure to ionizing radiation is expressed in terms of *absorbed dose,* which is the amount of energy imparted to matter per unit mass. Often simply called *dose,* it is a fundamental concept in measuring and quantifying the effects of exposure to radiation. The unit of absorbed dose is the *rad.* The different types of radiation mentioned above have different effects in damaging the cells of biological systems. *Dose equivalent* is a concept that considers (1) the absorbed dose and (2) the relative effectiveness of the type of ionizing radiation in damaging biological systems, using a radiation-specific quality factor. The unit of dose equivalent is the *rem.* In quantifying the effects of radiation on humans, other types of concepts are also used. The concept of *effective dose equivalent* is used to quantify effects of radionuclides in the body. It involves estimating the susceptibility of the different tissue in the body to radiation to produce a tissue-specific weighting factor. The weighting factor is based on the susceptibility of that tissue to cancer. The sum of the products of each affected tissue's estimated dose equivalent multiplied by its specific weighting factor is the *effective dose equivalent.* The potential effects from a one-time ingestion or inhalation of radioactive material are calculated over a period of 50 years to account for radionuclides that have long half-lives and long residence time in the body. The result is called the *committed effective dose equivalent.* The unit of effective dose equivalent is also the *rem. Total effective dose equivalent* is the sum of the committed effective dose equivalent from radionuclides in the body plus the dose equivalent from radiation sources external to the body (also in rem). All estimates of dose presented in this environmental impact statement, unless specifically noted as something else, are total effective dose equivalents, which are quantified in terms of rem or millirem (which is one one-thousandth of a rem).

More detailed information on the concepts of radiation dose and dose equivalent are presented in publications of the National Council on Radiation Protection and Measurements (NCRP 1993, page 16-25) and the International Commission on Radiological Protection (ICRP 1991, page 4-11). The DOE implementation guide for occupational exposure assessment (DOE 1998a, pages 3 to 11) also provides additional information.

The factors used to convert estimates of radionuclide intake (by inhalation or ingestion) to dose are called *dose conversion factors*. The National Council on Radiation Protection and Measurements and Federal agencies such as the U.S. Environmental Protection Agency publish these factors (NCRP 1996, all; Eckerman and Ryman 1993, all; Eckerman, Wolbarst, and Richardson 1988, all). They are based on original recommendations of the International Commission on Radiological Protection (ICRP 1977, all).

The radiation dose to an individual or to a group of people can be expressed as the total dose received or as a dose rate, which is dose per unit time (usually an hour or a year).

Collective dose is the total dose to an exposed population. *Person-rem* is the unit of collective dose. Collective dose is calculated by summing the individual dose to each member of a population. For example, if 100 workers each received 0.1 rem, then the collective dose would be 10 person-rem (100 × 0.1 rem).

Exposures to radiation or radionuclides are often characterized as being acute or chronic. Acute exposures occur over a short period of time, typically 24 hours or less. Chronic exposures occur over longer times (months to years); they are usually assumed to be continuous over a period, even though the dose rate might vary. For a given dose of radiation, chronic radiation exposure is usually less harmful than acute exposure because the dose rate (dose per unit time, such as rem per hour) is lower, providing more opportunity for the body to repair damaged cells.

F.1.1.4 Background Radiation from Natural Sources

Nationwide, on average, members of the public are exposed to approximately 360 millirem per year from natural and manmade sources (Gotchy 1987, page 53). Figure F-1 shows the relative contributions by radiation sources to people living in the United States (Gotchy 1987, page 55).

The estimated average annual dose rate from natural sources is only about 300 millirem per year. This represents about 80 percent of the annual dose received by an average member of the U.S. public. The largest natural sources are radon-222 and its radioactive decay products in homes and buildings, which contribute about 200 millirem per year. Additional natural sources include radioactive material in the Earth (primarily the uranium and thorium decay series, and potassium-40) and cosmic rays from space filtered through the atmosphere. With respect to exposures resulting from human activities, medical exposure accounts for 15 percent of the annual dose, and the combined doses from weapons testing fallout, consumer and industrial products, and air travel (cosmic radiation) account for the remaining 3 percent of the total annual dose. Nuclear fuel cycle facilities contribute less than 0.1 percent (0.005 millirem per year per person) of the total dose (Gotchy 1987, pages 53 to 55).

F.1.1.5 Impacts to Human Health from Exposure to Radiation

Chronic Exposure

Cancer is the principal potential risk to human health from exposure to low or chronic levels of radiation. This EIS expresses radiological health impacts as the incremental changes in the number of expected fatal cancers (latent cancer fatalities) for populations and as the incremental increases in lifetime probabilities of contracting a fatal cancer for an individual. The estimates are based on the dose received and on dose-to-health effect conversion factors recommended by the International Commission on Radiological Protection (ICRP 1991, page 22). The Commission estimated that, for the general population, a collective dose of 1 person-rem will yield 0.0005 excess latent cancer fatality. For radiation workers, a collective dose of 1 person-rem will yield an estimated 0.0004 excess latent cancer fatality. The higher risk factor for the general population is primarily due to the inclusion of children in the population group, while the radiation worker population includes only people older than 18. These risk coefficients were adopted by the National Council on Radiation Protection and Measurements in 1993 (NCRP 1993, page 3).

Other health effects such as nonfatal cancers and genetic effects can occur as a result of chronic exposure to radiation. Inclusion of the incidence of nonfatal cancers and severe genetic effects from radiation exposure increases the total change by a factor of 1.5 to 5, compared to the change for latent cancer fatalities (ICRP 1991, page 22). As is the general practice for any DOE EIS, estimates of the total change were not included in the Yucca Mountain EIS.

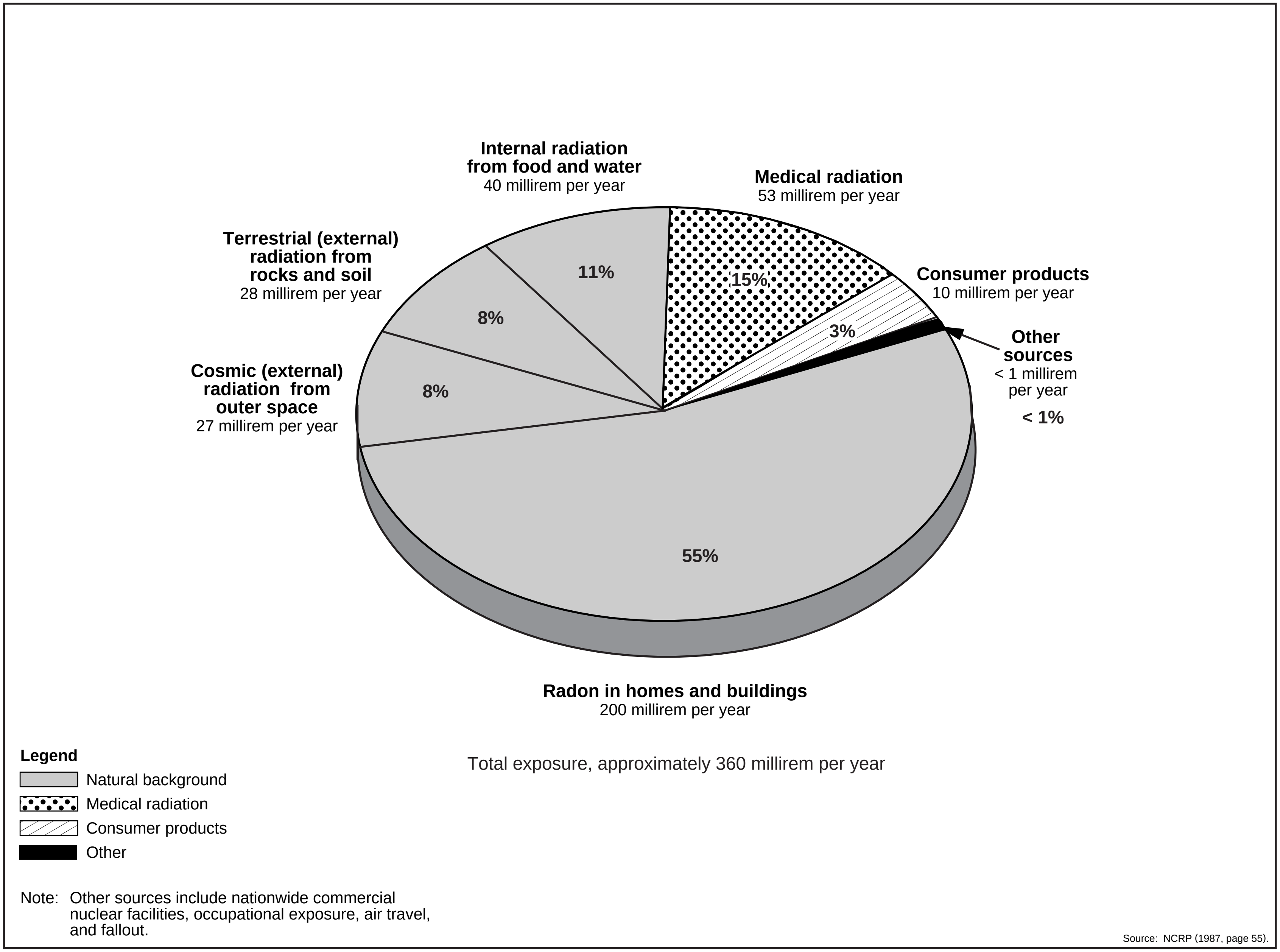

Figure F-1. Sources of radiation exposure.

Acute Exposure

Exposures to high levels of radiation at high dose rates over a short period (less than 24 hours) can result in acute radiation effects. Minor changes in blood characteristics might be noted at doses in the range of 25 to 50 rad. The external symptoms of radiation sickness begin to appear following acute exposures of about 50 to 100 rad and can include anorexia, nausea, and vomiting. More severe symptoms occur at higher doses and can include death at doses higher than 200 to 300 rad of total body irradiation, depending on the level of medical treatment received. Information on the effects of acute exposures on humans was obtained from studies of the survivors of the Hiroshima and Nagasaki bombings and from studies following a multitude of acute accidental exposures (Mettler and Upton 1995, pages 276 to 280).

Factors to relate the level of acute exposure to health effects exist but are not applied in this EIS because expected exposures during normal operations for the Proposed Action (including transportation), and for accident scenarios during the Proposed Action and the associated transportation activities, would be well below 50 rem. See Appendix J for exposures from accident scenarios during transportation activities.

F.1.1.6 Exposures from Naturally Occurring Radionuclides in the Subsurface Environment

The estimates of worker doses from inhalation of radon-222 and its decay products while in the subsurface environment and from the ambient radiation fields in the subsurface environment were based on measurements taken in the existing Exploratory Studies Facility drifts. The measurements and the annual dose rates derived from them are discussed below.

Annual Dose Rate for Subsurface Facility Worker from Inhalation of Radon-222

The annual dose rate for a subsurface worker from inhalation of radon-222 and radon decay products was estimated using site-specific measurements of the concentrations of radon-222 and its decay products in the Yucca Mountain Exploratory Studies Facility drifts. Measurements were made at a number of locations in the drifts (TRW 1999a, page 12). After examination of the data from various locations, the measurements taken at the 5,035-meter (about 16,500-foot) station in the main drift, with the ventilation system operating, were determined to provide the best basis for estimating the concentration of radon-222 in the subsurface atmosphere during the various Yucca Mountain Repository phases (TRW 1999a, page 12). The measured concentrations ranged from 0.22 to 72 picocuries per liter, with a median value of 6.5 picocuries per liter.

For each project phase, the measured average value (6.5 picocuries per liter) was adjusted to take into account the difference between the average air residence time in the repository at the time of measurement of radon-222 concentration and the average air residence time for a specific project phase. The average air residence time is the average volume being ventilated divided by the average ventilation rate for a project phase. For example, an increased repository volume would result in an increased average residence time as would a decrease in the ventilation flow rate.

Also considered were (1) the distribution of the measured values of the equilibrium fraction between radon-222 and the decay products in the underground facility; this value ranged from 0.0022 to 0.44, with a median of 0.14 (TRW 1999a, page 12); and (2) the number of hours an involved worker would be underground, exposed to airborne radon. Based on a typical amount of time spent underground (about 6.5 hours per workday) (Jessen 1999, all), the yearly exposure time for involved workers would range from 1,500 to 1,700 hours per year. The dose conversion factor for radon was taken from Publication 65 of the International Commission on Radiological Protection (ICRP 1994, page 24). This dose conversion factor, which is 0.5 rem per working-level month for inhalation of radon decay products by workers, corresponds to 0.029 millirem per picocurie per liter per hour for radon decay products in 100-percent equilibrium (equilibrium factor of 1.0) with the radon-222 parent (ICRP 1994, page 5). For radon products with a 0.14 equilibrium factor, the dose conversion factor would be 0.0041 millirem per picocurie per liter per hour.

The estimated baseline median dose to an involved worker in the Exploratory Studies Facility from inhalation of radon and radon decay products was estimated to be approximately 60 millirem per year. This estimate was used in calculating the worker dose estimates in this appendix. The estimated 5th-percentile dose is 2 millirem per year, and the 95th-percentile dose is 580 millirem per year. These estimates were made using a Monte Carlo uncertainty analysis.

Annual Dose for Subsurface Facility Worker from Ambient External Radiation in Drifts

Workers in the underground facility would also be exposed to external radiation from naturally occurring primordial radionuclides in the rock. Measured exposure rates for the underground facility ranged from 0.014 to 0.038 millirem per hour (TRW 1999a, page 12). As for inhalation dose estimates, an underground exposure time of 1,500 to 1,700 hours per year was considered. The estimated baseline median dose to an involved worker in the Exploratory Studies Facility from ambient external radiation would be approximately 40 millirem per year. This estimate was used in this appendix for calculating the worker dose estimates from ambient external radiation. The estimated 5th-percentile dose is 23 millirem per year, and the 95th-percentile dose is 56 millirem per year. Like the radon dose estimates, these estimates were made using a Monte Carlo uncertainty analysis.

F.1.2 EXPOSURE TO TOXIC OR HAZARDOUS MATERIALS

When certain natural or manmade materials or substances have harmful effects that are not random or do not occur solely at the site of contact, the materials or substances are described as toxic. Toxicology is the branch of science dealing with the toxic effects that chemicals or other substances might have on living organisms.

Chemicals can be toxic for many reasons, including their ability to cause cancer, to harm or destroy tissue or organs, or to harm body systems such as the reproductive, immune, blood-forming, or nervous systems. The following list provides examples of substances that can be toxic:

- Carcinogens, which are substances known to cause cancer in humans or in animals. If cancers have been observed in animals, they could occur in humans. Examples of generally accepted human carcinogens include asbestos, benzene, and vinyl chloride (Kamrin 1988, pages 37 and 38 and Chapter 6).

- Chemicals that controlled studies have shown to cause a harmful or fatal effect. Examples include metals such as cadmium, lead, and mercury; strong acids such as nitric acid and sulfuric acid; some welding fumes; coal dust; sulfur dioxide; and some solvents.

- Some biological materials, including various body fluids and tissues and infectious agents, are toxic.

Even though chemicals might be toxic, many factors influence whether or not a particular substance has a toxic effect on humans. These factors include (1) the amount of the substance with which the person comes in contact, (2) whether the person inhales or ingests a relatively large amount of the substance in a short time (acute exposure) or repeatedly ingests or inhales a relatively small amount over a longer time (chronic exposure), and (3) the period of time over which the exposure occurs.

Scientists determine a substance's toxic effect (or toxicity) by performing controlled tests on animals. In addition to environmental and physical factors, these tests help establish three other important factors for measuring toxicity—dose-response relationship, threshold concept, and margin of safety. The dose-response relationship relates the percentage of test animals that experience observable toxic effects to the doses administered. After the administration of an initial dose, the dose is increased or decreased until, at the upper end, all animals are affected and, at the lower end, no animals are affected. Thus, there is a threshold concentration below which there is no effect. The margin of safety is an arbitrary separation between the highest concentration or exposure level that produces no adverse effect in a test animal species and the concentration or exposure level designated safe for humans. There is no universal margin of safety. For some chemicals, a small margin of safety is sufficient; others require a larger margin.

Two substances in the rock at Yucca Mountain, crystalline silica and erionite, are of potential concern as toxic or hazardous materials. Both of these naturally occurring compounds occur in the parent rock at the repository site, and excavation activities could encounter them. The following paragraphs contain additional information on these.

Crystalline Silica

Crystalline silica is a naturally occurring, highly structured form of silica (silicon dioxide, SiO_2). Because it can occur in several different forms, including quartz, cristobalite, and tridymite, it is called a *polymorph*. These three forms occur in the welded tuff parent rock at Yucca Mountain (DOE 1998b, page 25). Crystalline silica is a known causative agent for *silicosis*, a destructive lung condition caused by deposition of particulate matter in the lungs and characterized by scarring of lung tissue. It is contracted by prolonged exposure to high levels of respirable silica dust or an acute exposure to even higher levels of respirable silica dust (EPA 1996, Chapter 8). Accordingly, DOE considers worker inhalation of respirable crystalline silica dust particles to be hazardous to worker health. Current standards for crystalline silica have been established to prevent silicosis in workers.

Cristobalite has a lower exposure limit than does quartz. The limits for these forms of silica include the Permissible Exposure Limits established by the Occupational Safety and Health Administration and the Threshold Limit Value defined by the American Conference of Governmental Industrial Hygienists. The Occupational Safety and Health Administration Permissible Exposure Limit is 50 micrograms per cubic meter averaged over a 10-hour work shift. The American Conference of Governmental Industrial Hygienists Threshold Limit Value is also 50 micrograms per cubic meter, but it is averaged over an 8-hour work shift (NJDHSS 1996, all). Thus, the two limits are essentially the same. In accordance with DOE Order 440.1A (DOE 1998a, page 5), the more restrictive value provided by the American Conference of Governmental Industrial Hygienists will be applied. In addition, the National Institute for Occupational Safety and Health has established Immediately-Dangerous-to-Life-and-Health concentration limits at levels of 50,000 and 25,000 micrograms per cubic meter for quartz and cristobalite, respectively (NIOSH 1996, page 2). These limits are based on the maximum airborne concentrations an individual could tolerate for 30 minutes without suffering symptoms that could impair escape from the contaminated area or irreversible acute health effects.

There is also evidence that silica may be a carcinogen. The International Agency for Research on Cancer has classified crystalline silica and cristobalite as a Class I (known) carcinogen (IARC 1997, pages 205 to 210). The National Institute for Occupational Safety and Health considers crystalline silica to be a potential carcinogen, as defined by the Occupational Safety and Health Administration's carcinogen policy (29 CFR Part 1990). The National Institute for Occupational Safety and Health is reviewing data on carcinogenicity, which could result in a revised limit for crystalline silica. The Environmental Protection Agency has noted an increase in cancer risk to humans who have already developed the adverse noncancer effects of silicosis, but the cancer risk to otherwise healthy individuals is not clear (EPA 1996, pages 1 to 5).

Because there are no specific limits for exposure of members of the public to crystalline silica, this analysis used a comparative benchmark of 10 micrograms per cubic meter, based on a cumulative lifetime exposure limit of 1,000 micrograms per (cubic meter multiplied by years). At this level, an Environmental Protection Agency health assessment has stated that there is a less than 1 percent chance of silicosis (EPA 1996, Chapter 1, page 5, and Chapter 7, page 5). Over a 70-year lifetime, this cumulative exposure benchmark would correspond to an annual average exposure concentration of about 14 micrograms per cubic meter, which was rounded down to 10 micrograms per cubic meter to establish the benchmark. Appendix G, Section G.1 contains additional information on public exposure to crystalline silica.

Samples of the welded tuff parent rock from four boreholes at Yucca Mountain have an average quartz content of 15.7 percent, an average cristobalite content of 16.3 percent, and an average tridymite content of 3.5 percent (DOE 1998b, page I-1). Worker protection during excavation in the subsurface would be based on the more restrictive Threshold Limit Value for cristobalite. The analysis assumed that the parent rock and dust would have a cristobalite content of 28 percent, which is the higher end of the concentration range reported in TRW (1999b, page 4-81). Thus, the assumed percentage of cristobalite in dust probably will overestimate the airborne cristobalite concentration. Also, studies of both ambient and occupational airborne crystalline silica have shown that most of the airborne crystalline silica is coarse and not respirable (greater than 5 micrometers aerodynamic diameter), and the larger particles will deposit rapidly on the surface (EPA 1996, page 3-26).

Erionite

Erionite is a natural fibrous zeolite that occurs in the rock layers below the proposed repository level in the hollows of rhyolitic tuffs and in basalts. It might also occur in rock layers above the repository level but has not been found in those layers. Erionite is a rare tectosilicate zeolite with hexagonal symmetry that forms wool-like fibrous masses (with a maximum fiber length of about 50 microns, which is generally shorter than asbestos fibers). Erionite particles (ground to powder) resemble amphibole asbestos fibers. Erionite fibers have been detected in samples of road dust in Nevada, and residents of the Intermountain West could be exposed to fibrous erionite in ambient air (Technical Resources 1994, page 134).

There are no specific limits for exposure to erionite. Descriptive studies have shown very high mortality from cancer [malignant mesothelioma, mainly of the pleura (a lung membrane)] in the population of three Turkish villages in Cappadocia where erionite is mined. The International Agency for Research on Cancer has indicated that these studies demonstrate the carcinogenicity of erionite to humans. The Agency classifies erionite as a Group 1 (known) carcinogen (IARC 1987, all).

Erionite could become a potential hazard during excavation of access tunnels to the lower block and to offset Area 5 for the low and intermediate thermal load cases or during vertical boring operations necessary to excavate ventilation shafts. DOE does not expect to encounter erionite layers during the vertical boring operations, which would be through rock layers above known erionite layers, or during excavation of access tunnels to the lower block or offset Area 5, where any identified layers of erionite would likely be avoided (McKenzie 1998, all). In accordance with the Erionite Protocol (DOE 1995, all), a task-specific health and safety plan would be prepared before the start of boring operations to identify this material and prevent worker inhalation exposures from unconfined material.

The Los Alamos National Laboratory is studying the mineralogy and geochemistry of the deposition of erionite under authorization from the DOE Office of Energy Research. Laboratory researchers are applying geochemical modeling so they can understand the factors responsible for the formation of zeolite assemblages in volcanic tuffs. The results of this modeling will be used to predict the distribution of erionite at Yucca Mountain and to assist in the planning of excavation operations so erionite layers are avoided.

F.1.3 EXPOSURE PATHWAYS

Four conditions must exist for there to be a pathway from the source of released radiological or toxic material to a person or population (Maheras and Thorne 1993, page 1):

- A source term: The material released to the environment, including the amount of radioactivity (if any) or mass of material, the physical form (solid, liquid, gas), particle size distribution, and chemical form

- An environmental transport medium: Air, surface water, groundwater, or a food chain

- An exposure route: The method by which a person can come in contact with the material (for example, external exposure from contaminated ground, immersion in contaminated air or internal exposure from inhalation or ingestion of radioactive or toxic material)

- A human receptor: The person or persons potentially exposed; the level of exposure depends on such factors as location, duration of exposure, time spent outdoors, and dietary intake

These four elements define an exposure pathway. For example, one exposure scenario might involve release of contaminated gas from a stack (source term); transport via the airborne pathway (transport medium); external gamma exposure from the passing cloud (exposure route); and an onsite worker (human receptor). Another exposure scenario might involve a volatile organic compound as the source term, release to groundwater as the transport medium, ingestion of contaminated drinking water as the exposure route, and offsite members of the public as the human receptors. No matter which pathway the scenario involves, local factors such as water sources, agriculture, and weather patterns play roles in determining the importance of the pathway when assessing potential human health effects.

Worker exposure to crystalline silica (and possibly erionite) in the subsurface could occur from a rather unique exposure pathway. Mechanical drift excavation, shaft boring, and broken rock management activities could create airborne dust comprising a range of particles sizes. Dust particles smaller than 10 micrometers have little mass and inertia in comparison to their surface area; therefore, these small particles could remain suspended in dry air for long periods. Airborne dust concentrations could increase if the ventilation system recirculated the air or if airflow velocity in the subsurface facilities became high enough to entrain dust previously deposited on drift or equipment surfaces. As tunnel boring machines or road headers break the rock from the working face, water would be applied to wet both the working face and the broken rock to minimize airborne dust levels. Wet or dry dust scrubbers would capture dust that was not suppressed by the water sprays. To prevent air recirculation, which would lead to an increase of airborne dust loads, the fresh air intake and the exhaust air streams would be separated. Finally, the subsurface ventilation system would be designed and operated to control ambient air velocities to minimize dust reentrainment. If these engineering controls did not maintain dust concentrations below the Threshold Limit Value concentration, workers would have to wear respirators until engineering controls established habitable conditions.

F.2 Human Health and Safety Impact Analysis for the Proposed Action Inventory

This section discusses the methodologies and data used to estimate industrial and radiological health and safety impacts to workers that would result from the construction, operation and monitoring, and closure of the Yucca Mountain Repository, as well as the detailed results from the impact calculations. Section F.2.1 describes the methods used to estimate impacts, Section F.2.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources, and Section F.2.3 contains a detailed tabulation of results.

For members of the public, the EIS uses the analysis methods in Appendix K, Section K.2, to estimate radiation dose from radon-222 and crystalline silica released in the subsurface ventilation system exhaust. The radiation dose estimates were converted to estimates of human health impacts using the dose conversion factors discussed in Section F.1.1.5. These impacts are expressed as the probability of a latent cancer fatality for a maximally exposed individual and as the number of latent cancer fatalities among members of the public within about 80 kilometers (50 miles) for the Proposed Action, the retrieval contingency, and the inventory modules. The results are listed in Chapter 4, Section 4.1.7.

Health and safety impacts to workers have been estimated for two worker groups: involved workers and noninvolved workers. Involved workers are craft and operations personnel who would be directly involved in activities related to facility construction and operations, including excavation activities; receipt, handling, packaging, and emplacement of spent nuclear fuel and high-level radioactive waste material; monitoring of conditions and performance of the waste packages; and those directly involved in closure activities. Noninvolved workers are managerial, technical, supervisory, and administrative personnel who would not be directly involved in construction, excavation, operations, monitoring, and closure activities. The analysis did not consider project workers who would not be located at the repository site.

F.2.1 METHODOLOGY FOR CALCULATING OCCUPATIONAL HEALTH AND SAFETY IMPACTS

To estimate the impacts to workers from industrial hazards common to the workplace, values for the full-time equivalent work years for each phase of the project were multiplied by the statistic (occurrence per 10,000 full-time equivalent work years) for the impact being considered. Values for the number of full-time equivalent workers for each phase of the project are listed in Section F.2.2.1. The statistics for industrial impacts for each of the phases are listed in Section F.2.2.2 for involved and noninvolved workers.

Two kinds of radiological health impacts to workers are provided in this EIS. The first is an estimate of the latent cancer fatalities to the worker group involved in a particular project phase. The second is the incremental increase in latent cancer fatalities attributable to occupational radiation for a maximally exposed individual in the worker population for each project phase.

To calculate the expected number of worker latent cancer fatalities during a phase of the project, the collective dose to the worker group, in person-rem, was multiplied by a standard factor for converting the collective worker dose to projected latent cancer fatalities (see Section F.1.1.5). As discussed in Section F.1.1.5, the value of this factor for radiation workers is 0.0004 excess latent cancer fatality per person-rem of dose.

The collective dose for a particular phase of the operation is calculated as the product of the number of full-time equivalent workers for the project phase (see Section F.2.2.1), the average dose over the exposure period, and the fraction of the working time that a worker is in an environment where there is a source of radiation exposure. Values for exposure rates for both involved and noninvolved workers are presented in Section F.2.2.3 as are the fractional occupancy factors. The calculation of collective dose to subsurface workers from exposure to the radiation emanating from the loaded waste packages is an exception. Collective worker doses from this source of exposure were calculated using the methodology described in TRW (1999b, Tables G-1 and G-2). For the calculation of exposures, the estimated annual radiation doses listed in TRW (1999b, Tables G-3, G-3a, G-4, and G-4a) for the various classes of involved subsurface workers were used. The exposure values were multiplied by the craft manpower distribution listed in TRW (1999b, Tables G-5, G-5a, G-5b, G-7, G-7a, and G-7b) for each of the involved labor classes for a project phase to obtain an overall annual exposure. The annual exposures for the labor classes were then summed to obtain the collective annual dose in person-rem to the involved subsurface workers for each of the subsurface operational phases. The total collective dose was then obtained by multiplying the annual collective dose by the length of the project phase.

To estimate the incremental increase in the likelihood of death from a latent cancer for the maximally exposed individual, the estimated dose to the maximally exposed worker was multiplied by the factor for converting radiation dose to latent cancers. The factor applied for workers was 0.0004 latent cancer fatality per rem, as discussed above and in Section F.1.1.5. Thus, if a person were to receive a dose of 1 rem, the incremental increase in the probability that person would suffer a latent cancer fatality is 1 in 2,500 or 0.0004.

To estimate the dose for a hypothetical maximally exposed individual, the analysis generally assumed that this individual would be exposed to the radiation fields (see Section F.2.2.3) over the entire duration of a project phase or for 50 years, whichever would be shorter. Other sources of exposure while working underground would be ambient radiation coming from the radionuclides in the drift walls and from inhalation of radon-222 and its decay products. The radiation from the waste package is usually the dominant component when these three dose contributors are added. Doses for the maximally exposed subsurface worker were estimated by adding the three dose components because they would occur simultaneously.

F.2.2 DATA SOURCES AND TABULATIONS

F.2.2.1 Work Hours for the Repository Phases

Table F-1 lists the number of workers involved in the various repository phases in terms of full-time equivalent work years. Each full-time equivalent work year represents 2,000 work hours (the number of hours assumed for a normal work year). The values were obtained from TRW (1999c, Section 6) and from TRW (1999b, Section 6) for surface and subsurface workers, respectively.

F.2.2.2 Workplace Health and Safety Statistics

The analysis selected health and safety statistics for three impact categories—total recordable cases, lost workday cases, and fatalities. Total recordable cases are occupational injuries or illnesses that result in:

- Fatalities, regardless of the time between the injury and death, or the length of the illness
- Lost workday cases, other than fatalities, that result in lost workdays
- Nonfatal cases without lost workdays that result in transfer to another job, termination of employment, medical treatment (other than first aid), loss of consciousness, or restriction of work or motion
- Diagnosed occupational illness cases that are reported to the employer but are not classified as fatalities or lost workday cases

Table F-1. Estimated full-time equivalent worker years for repository phases.

Phase	Subphase or worker group	Source[a]	Length of phase	High thermal load			Intermediate thermal load			Low thermal load		
				UC[b]	DISP[c]	DPC[d]	UC	DISP	DPC	UC	DISP	DPC
Construction	Surface	(1)	44 months									
	Involved			2,380	1,650	1,760	2,380	1,650	1,760	2,380	1,650	1,760
	Noninvolved			900	630	670	900	630	670	900	630	670
	Subsurface	(2)	5 years									
	Involved			2,300	2,300	2,300	2,460	2,460	2,460	2,460	2,460	2,460
	Noninvolved			600	600	600	600	600	600	600	600	600
	Construction subtotal			*6,180*	*5,180*	*5,330*	*6,340*	*5,340*	*5,490*	*6,340*	*5,340*	*5,490*
Operation and monitoring												
Operations	Surface handling	(3)	24 years									
	Involved			17,500	11,470	11,810	17,500	11,470	11,810	17,500	11,470	11,810
	Noninvolved			13,150	11,620	11,760	13,150	11,620	11,760	13,150	11,620	11,760
	Subsurface emplacement	(4)	24 years									
	Involved			1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780	1,780
	Noninvolved			380	380	380	380	380	380	380	380	380
	Subsurface development	(5)	(e)									
	Involved			6,230	6,230	6,230	6,230	6,230	6,230	6,530	6,530	6,530
	Noninvolved		22 years	1,670	1,670	1,670	1,670	1,670	1,670	1,670	1,670	1,670
	Operations subtotal			*40,710*	*33,150*	*33,630*	*40,710*	*33,150*	*33,630*	*41,010*	*33,450*	*33,930*
Monitoring	Surface	(6)	76 years									
	Involved			2,260	2,260	2,260	2,260	2,260	2,260	2,260	2,260	2,260
	Noninvolved			NA[f]	NA	NA	NA	NA	NA	NA	NA	NA
	Surface decontamination	(7)	3 years									
	Involved			4,060	2,950	3,070	4,060	2,950	3,070	4,060	2,950	3,070
	Noninvolved			NA	NA	NA	NA	NA	NA	NA	NA	NA
	Subsurface	(8)	76 years									
	Involved			5,240	5,240	5,240	5,240	5,240	5,240	5,780	5,780	5,780
	Noninvolved			990	990	990	990	990	990	990	990	990
	Monitoring subtotal			*12,550*	*11,440*	*11,560*	*12,550*	*11,440*	*11,560*	*13,090*	*11,980*	*12,100*
Operation and monitoring subtotal				*53,260*	*44,590*	*45,190*	*53,260*	*44,590*	*45,190*	*54,500*	*45,430*	*46,030*
Closure	Surface	(9)	6 years									
	Involved			1,580	1,110	1,200	1,580	1,110	1,210	1,580	1,110	1,200
	Noninvolved			600	420	460	600	420	460	600	420	460
	Subsurface	(10)	(g)									
	Involved			1,310	1,310	1,310	1,310	1,310	1,310	3,270	3,270	3,270
	Noninvolved			260	260	260	260	260	260	660	660	660
	Closure subtotal			*3,750*	*3,100*	*3,230*	*3,750*	*3,100*	*3,230*	*6,110*	*5,460*	*5,590*
Totals				***63,190***	***52,870***	***53,750***	***63,350***	***53,030***	***53,910***	***66,940***	***56,230***	***57,110***

a. Sources: (1) TRW (1999c, Table 6-1); (2) TRW (1999b, Table 6.1.1.1-1); (3) TRW (1999c Table 6-2); (4) TRW (1999b, Table 6.1.3.1-1); (5) TRW (1999b, Table 6.1.2.1-1); (6) TRW (1999c, Table 6-5); (7) TRW (1999c, Table 6-4); (8) TRW (1999b, Table 6.1.4.1-1); (9) TRW (1999c, Table 6-6); (10) TRW (1999b, Table 6.1.6.1-1).
b. UC = uncanistered packaging scenario.
c. DISP = disposable canister packaging scenario.
d. DPC = dual-purpose canister packaging scenario.
e. High thermal load and intermediate thermal load = 21 years; low thermal load = 22 years.
f. NA = not applicable.
g. High thermal load = 6 years; intermediate thermal load = 6 years; low thermal load = 15 years.

Lost workday cases, which are described above, include cases that result in the loss of more than half a workday. These statistical categories, which have been standardized by the U.S. Department of Labor and the Bureau of Labor Statistics, must be reported annually by employers with 11 or more employees. Table F-2 summarizes the health and safety impact statistics used for this analysis.

Table F-2. Health and safety statistics for estimating industrial safety impacts common to the workplace.[a]

Phase	Total recordable cases incidents per 100 FTEs[b]		Lost workday cases per 100 FTEs		Fatalities per 100,000 FTEs (involved and noninvolved)[c]	Data set for TRCs and LWCs[d]
	Involved	Noninvolved	Involved	Noninvolved		
Construction						
Surface	6.1	3.3	2.9	1.6	2.9	(1)
Subsurface	6.1	3.3	2.9	1.6	2.9	(1)
Operation and Monitoring						
Operation period						
Surface	3	3.3	1.2	1.6	2.9	(3)
Subsurface - emplacement	3	3.3	1.2	1.6	2.9	(3)
Subsurface - drift development	6.8	1.1	4.8	0.7	2.9	(2)
Monitoring period						
Surface	3	3.3	1.2	1.6	2.9	(3)
Subsurface	3	3.3	1.2	1.6	2.9	(3)
Closure						
Surface	6.1	3.3	2.9	1.6	2.9	(1)
Subsurface	6.1	3.3	2.9	1.6	2.9	(1)

a. See text below for source of data in Data Sets 1, 2, and 3.
b. FTEs = full-time equivalent work years.
c. See the discussion about Data Set 4 for source of fatality statistic for normal industrial activities.
d. TRCs = total recordable cases; LWCs = lost workday cases.

Table F-2 cites three sets of statistics that were used to estimate total recordable cases and lost workday cases for workers during activities at the Yucca Mountain site. In addition, there is a fourth statistic related to the occupational fatality projections for the Yucca Mountain site activities. The source of information from which the sets of impact statistics were derived is discussed below. All of the statistics are based on DOE experience for similar types of activities and were derived from the DOE CAIRS (Computerized Accident/Incident Reporting and Recordkeeping System) data base (DOE 1999, all).

Data Set 1, Construction and Construction-Like Activities

This set of statistics from the DOE CAIRS data base was applied to construction or construction-like activities. Specifically, it was used for both surface and subsurface workers during the construction phase and the closure phase (closure phase activities were deemed to be construction-like activities). The statistics were based on a 6.75-year period (1992 through the third quarter of 1998).

For involved workers the impact statistic numbers were derived from the totals for all of the DOE construction activities over the period. For noninvolved workers, the values were derived from the combined government and services contractor noninvolved groups for the same period. The noninvolved worker statistic, then, is representative of impacts for oversight personnel who would not be involved in the actual operation of equipment or resources. The basic statistics derived from the CAIRS data base for each of the groups include:

- Involved worker total recordable cases: 764 recordable cases for approximately 12,400 full-time equivalent work years
- Involved worker lost workday cases: 367 lost workday cases for approximately 12,400 full-time equivalent work years
- Noninvolved worker total recordable cases: 1,333 recordable cases for approximately 40,600 full-time equivalent work years
- Noninvolved worker lost workday cases: 657 lost workday cases for approximately 40,600 full-time equivalent work years

Data Set 2, Excavation Activities

This set of statistics was derived from experience at the Yucca Mountain Project over a 30-month period (fourth quarter of 1994 though the first quarter of 1997). DOE selected this period because it coincided with the exploratory tunnel boring machine operations at Yucca Mountain, reflecting a high level of worker activity during ongoing excavation activities. This statistic was applied for the Yucca Mountain Project subsurface development period, which principally involves drift development activities. The Yucca Mountain Project experience from which the statistic is derived is presented in Table F-3. Stewart (1998, all) contains the Yucca Mountain statistics, which were derived from the CAIRS data base (DOE 1999, all).

Table F-3. Yucca Mountain Project worker industrial safety loss experience.[a]

Factor	Value[b]	Basis
TRCs[c] per 100 FTEs[d]		
Involved worker	6.8	56 TRCs for 825 construction FTEs
Noninvolved worker	1.1	2.3 TRCs for 2,015 nonconstruction FTEs
LWCs[e] per 100 FTEs		
Involved worker	4.8	40 LWCs for 825 construction FTEs
Noninvolved worker	0.7	14 LWCs for 2,015 nonconstruction FTEs
Fatality rate occurrence per 100,000 FTEs		
Involved worker	0.0	No fatalities for 825 construction FTEs
Noninvolved worker	0.0	No fatalities for 2,015 nonconstruction FTEs

a. Fourth quarter 1994 through first quarter 1997.
b. Source: Adapted from the CAIRS data base (DOE 1999, all) by Stewart (1998, all) for the fourth quarter of 1994 through the first quarter of 1997.
c. TRCs = total recordable cases of injury and illness.
d. FTEs = full-time equivalent work years.
e. LWCs = lost workday cases.

Data Set 3, Activities Involving Work in a Radiological Environment

This set of statistics is from the DOE CAIRS data base (DOE 1999, all). In arriving at the statistics listed in Table F-2, information from the Savannah River Site, the Hanford Site, and the Idaho National Engineering and Environmental Laboratory was averaged individually for the 6.5 years from 1992 through the second quarter of 1998. The averages were then combined to produce an overall average. The reason these three sites were selected as the basis for this set of statistics is that the DOE Savannah River, Hanford, and Idaho National Engineering and Environmental Laboratory sites currently conduct most of the operations in the DOE complex involving handling, sorting, storing, and inspecting spent nuclear fuel and high-level radioactive waste materials, as well as similar activities for low-level radioactive waste materials. The Yucca Mountain Repository phases for which this set of statistics was applied included the receipt, handling, and packaging of spent nuclear fuel and high-level radioactive waste in the surface facilities; subsurface emplacement activities; and surface and subsurface monitoring activities, including decontamination of the surface facilities. These activities involve handling, storing, and inspecting spent nuclear fuel and high-level radioactive waste, so the worker activities at the Yucca Mountain site are expected to be similar to those cited above for the other sites in the DOE complex.

The basic statistics for the involved and noninvolved workers include:

- Involved worker total recordable cases: 1,246 for about 41,600 full-time equivalent work years
- Involved worker lost workday cases: 538 for about 41,600 full-time equivalent work years
- Noninvolved worker total recordable cases: 1,333 for about 40,600 full-time equivalent work years
- Noninvolved worker lost workday cases: 657 for about 40,600 full-time equivalent work years

Data Set 4, Statistics for Worker Fatalities from Industrial Hazards

There have been no reported fatalities as a result of workplace activities for the Yucca Mountain project. Similarly, there are no fatalities listed in the Mine Safety and Health Administration data base for stone mining workers (MSHA 1999, all). Because fatalities in industrial operations sometimes occur, the more extensive overall DOE data base was used to estimate a fatality rate for the activities at the Yucca Mountain site. Statistics for the DOE facility complex for the 10 years between 1988 and 1997 were used (DOE 1999, all). These fatality statistics are for both government and contractor personnel working in the DOE complex who were involved in the operation of equipment and resources (involved workers). The activities in the DOE complex covered by this statistic were governed by safety and administrative controls (under the DOE Order System) that are similar to the safety and administrative controls that would be applied for Yucca Mountain Repository work. These fatality statistics were also applied to the noninvolved worker population because they are the most inclusive statistics in the CAIRS data base. However, the statistics probably are conservatively high for the noninvolved worker group.

F.2.2.3 Estimates of Radiological Exposures

DOE considered the following potential sources of radiation exposure for assessing radiological health impacts to workers:

- Inhalation of gaseous radon-222 and its decay products. Subsurface workers could inhale the radon-222 present in the air in the repository drifts. Workers on the surface could inhale radon-222 released to the environment in the exhaust air from the subsurface ventilation system.

- External exposure of surface workers to radioactive gaseous fission products that could be released during handling and packaging of spent nuclear fuel with failed cladding for emplacement in the repository. Such impacts would be of most concern for the uncanistered shipping cask scenario.

- Direct external exposure of workers in the repository drifts as a result of naturally occurring radionuclides in the walls of the drifts (primarily potassium-40 and radionuclides of the naturally occurring uranium and thorium decay series).

- External exposure of workers to direct radiation emanating from the waste packages containing spent nuclear fuel and high-level radioactive waste either during handling and packaging (surface facility workers) or after it is placed within the waste package (largely subsurface workers).

Section F.1.1.6 describes the approach taken to estimate exposures to workers as a result of release of gaseous radon-222 from the drift walls to the subsurface atmosphere. For radon exposures to subsurface workers, the analysis assumed a subsurface occupancy factor of 1.0 for involved workers, an occupancy factor of 0.6 for noninvolved workers for construction and drift development activities, and an occupancy factor of 0.4 for noninvolved workers for emplacement, monitoring, and closure (Rasmussen 1998a, all; Rasmussen 1999, all; Jessen 1999, all).

As discussed in Section F.1.1.6, the average concentration of radon-222 in the subsurface atmosphere varies with the ventilation rate and repository volume. Table F-4 lists the correction factors (multipliers) applied to the average value for the concentration of radon-222 measured in the Exploratory Studies Facility for the Proposed Action.

Table F-4. Correction factors and annual exposures from radon-222 and its decay products for each of the project phases or periods under the Proposed Action.[a]

	Correction factor			Annual dose rate (millirem per year)		
	Thermal load scenario			Thermal load scenario		
Project phase or period	High	Intermediate	Low	High	Intermediate	Low
Construction	1.9	2.2	2.2	114	132	132
Drift development	0.6	0.6	0.6	36	36	36
Emplacement	1.1	1.5	2.9	66	90	174
Monitoring	3.2	4.1	4.4	192	246	264
Closure	3.2	4.1	4.4	192	246	264
Retrieval[b]	3.2	3.2	3.2	192	192	192

a. Based on the measured value of 60 rem per year corrected for repository volume and ventilation rate; see Section F.1.1.6 and Appendix G (Section G.2.3.1).

b. Multiplier for retrieval is not dependent on thermal load.

Appendix G, Section G.2.4.2 describes the approach taken to estimate source terms and associated doses to workers from the potential release of gaseous fission products from spent nuclear fuel with failed cladding.

Subsurface workers would also be exposed to background gamma radiation from naturally occurring radionuclides in the subsurface rock (largely from the uranium-238 decay series radionuclides and from potassium-40, both in the rock). DOE has based its projection of worker external gamma dose rates on the data obtained during Exploratory Studies Facility operations (Section F.1.1.6). The collective ambient radiation exposures for subsurface workers were calculated assuming occupancy factors cited in the previous paragraph for subsurface workers for emplacement and monitoring activities (Rasmussen 1998a, all; Rasmussen 1999, all; Jessen 1999, all).

Table F-5 lists dose rates in the fourth column for cases in which the annual full-time equivalent surface worker exposure values vary with the shipping package scenario. The table also lists the sources from which the data were obtained. The dose rates to subsurface workers from the radiation emitted from waste packages would vary with the thermal load, as indicated in the fourth column of Table F-5.

Table F-6 lists the annual exposures to subsurface workers from radiation emanating from the waste packages for the high, intermediate, and low thermal load scenarios, under the Proposed Action and Module 1 and 2 inventories. Section F.3 discusses Inventory Modules 1 and 2.

Table F-5. Radiological exposure data used to calculate worker radiological health impacts (page 1 of 2).

Phase and worker group	Exposure source[a]	Occupancy factor[b]	Annual dose (millirem, except where noted)	Annual full-time equivalent workers[c]			Data source[g]
				UC[d]	DISP[e]	DPC[f]	
Construction							
Surface							
Involved	Radon-222 inhalation	1.0	Small relative to subsurface worker exposures				(h)
Noninvolved	Radon-222 inhalation	1.0	Small relative to subsurface worker exposures				(h)
Subsurface							
Involved	Drift ambient	1.0	40				(1), (2)
	Radon-222 inhalation	1.0	Table F-4				(2), Table F-4
Noninvolved	Drift ambient	0.6	40				(1), (2)
	Radon-222 inhalation	0.6	Table F-4				(2), Table F-4
Operations and monitoring							
Surface handling and loading operations							
Involved	Receipt, handling and packaging of spent nuclear fuel and high-level radioactive waste	1.0	400 100	464 297	199 228	199 244	(3)
Noninvolved	Receipt, handling and packaging of spent nuclear fuel and high-level radioactive waste	1.0	25 0	175 341	150 386	149 390	(3)
Surface monitoring							
Involved only	Radon-222 inhalation	1.0	Small relative to subsurface workers				(i)
Surface decontamination (postemplacement, involved only)							
	External exposure	1.0	100	826	599	624	(4)
		1.0	25	528	383	399	(4)
Subsurface emplacement							
Involved	Waste package	Varies, see Table F-6	Varies, see Table F-6				Table F-6
	Drift ambient	1.0	40				(1), (2)
	Radon-222	1.0	Table F-4				(2), Table F-4
Noninvolved	Waste package	0.04	0.1 millirem per hour				(5)
	Drift ambient	0.4	40				(1), (2)
	Radon-222 inhalation	0.4	Table F-4				(2), Table F-4
Subsurface drift development							
Involved	Drift ambient	1.0	40				(1), (2)
	Radon-222 inhalation	1.0	Table F-4				(2), Table F-4
Noninvolved	Drift ambient	0.6	40				(1), (2)
	Radon-222 inhalation	0.6	Table F-4				(2), Table F-4
Monitoring							
Subsurface							
Involved	Waste package	Varies, see Table F-6	Varies, see Table F-6				Table F-6
	Drift ambient	1.0	40				(1), (2)
	Radon-222 inhalation	1.0	Table F-4				(2), Table F-4
Noninvolved	Waste package	0.04	0.1 millirem per hour				(5)
	Drift ambient	0.4	40				(1), (2), (6)
	Radon-222 inhalation	0.4	Table F-4				(2), (6), Table F-4

Table F-5. Radiological exposure data used to calculate worker radiological health impacts (page 2 of 2).

Phase and worker group	Exposure source[a]	Occupancy factor[b]	Annual dose (millirem per year except where noted)	Annual full-time equivalent workers[c] UC[d]	DISP[e]	DPC[f]	Data source[g]
Closure							
Surface							
Involved		1.0	Small relative to subsurface worker exposures				(j)
Noninvolved		1.0	Small relative to subsurface worker exposures				(j)
Subsurface							
Involved	Waste package	Varies, see Table F-6	Varies, see Table F-6				Table F-6
	Drift ambient	1.0	40				(1), (2)
	Radon-222 inhalation	1.0	Table F-4				(2), Table F-4
Noninvolved	Waste package	0.04	0.1 millirem per hour				(5)
	Drift ambient	0.4	40				(1), (2)
	Radon-22 inhalation	0.4	Table F-4				(2), Table F-4

a. Exposure sources include radiation from spent nuclear fuel and high-level radioactive waste packages to surface and subsurface workers, the ambient exposure to subsurface workers from naturally occurring radiation in the drift walls, and internal exposures from inhalation of radon-222 and its decay products in the drift atmosphere.
b. Fraction of 8-hour workday that workers are exposed.
c. Number of annual full-time equivalent workers for surface facility activities when number of workers would vary with shipping package scenario.
d. UC = uncanistered packaging scenario.
e. DISP = disposable canister packaging scenario.
f. DPC = dual-purpose canister packaging scenario.
g. Sources:
   (1) Section F.1.1.6.
   (2) Rasmussen (1998a, all).
   (3) TRW (1999c, Table 6-2).
   (4) Total employment for decontamination activities taken from TRW (1999c, Table 6-4). In Table 6-2 of TRW (1999c), the distribution of involved workers for surface facility receipt, handling, and packaging phase between the 400 millirem per year and 100 millirem per year cases is 61 percent and 39 percent, respectively. For decontamination operations it was assumed that 69 percent of the involved worker population would receive 100 millirem per year and 39 percent of the involved worker population would receive 25 millirem per year.
   (5) Rasmussen (1999, all).
   (6) Jessen (1999, all).
h. Comparison of information in Chapter 4, Table 4-2 (surface workers) and Table F-9 (subsurface workers).
i. Comparison of information in Chapter 4, Table 4-5 (surface workers) and Table F-27 (subsurface workers).
j. Comparison of information in Chapter 4, Table 4-7 (surface workers) and Table F-30 (subsurface workers).

Table F-6. Annual involved subsurface worker exposure rates from waste packages[a] (person-rem per year).

Project phase	Proposed Action High	Intermediate	Low	Inventory Modules High	Intermediate	Low
Emplacement	10.1	10.2	5.6	10.2	10.2	6.0
Monitoring	7.2	7.2	4.1	7.2	7.8	5.6
Closure	12.5	12.5	7.4	12.5	12.5	7.4

a. Sources: individual exposure values from TRW (1999b, Appendix G, Tables G-3, G-3a, G-4, and G-4a).
b. Calculated annual exposures, Rasmussen (1999, all).

F.2.3 COMPILATION OF DETAILED RESULTS FOR OCCUPATIONAL HEALTH AND SAFETY IMPACTS

F.2.3.1 Occupational Health and Safety Impacts During the Construction Phase

F.2.3.1.1 *Industrial Hazards to Workers*

Tables F-7 and F-8 list health and safety impacts from industrial hazards to surface and subsurface workers, respectively, for construction activities.

Table F-7. Industrial hazard health and safety impacts to surface facility workers during construction phase (44 months).[a]

Worker group	Waste packaging scenario		
	Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	2,380	1,650	1,760
Total recordable cases	150	100	110
Lost workday cases	70	50	50
Fatalities	0.07	0.05	0.05
Noninvolved			
Full-time equivalent work years	900	630	670
Total recordable cases	30	21	22
Lost workday cases	15	10	11
Fatalities	0.03	0.02	0.02
All workers (totals)[c]			
Full-time equivalent work years	3,280	2,280	2,420
Total recordable cases	180	120	130
Lost workday cases	85	59	63
Fatalities	0.10	0.07	0.07

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Table F-8. Industrial hazard health and safety impacts to subsurface facility workers during construction phase (5 years).[a]

Worker group	Thermal load scenario		
	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	2,300	2,460	2,460
Total recordable cases	140	150	150
Lost workday cases	68	72	72
Fatalities	0.07	0.07	0.07
Noninvolved			
Full-time equivalent work years	600	600	600
Total recordable cases	20	20	20
Lost workday cases	10	10	10
Fatalities	0.02	0.02	0.02
All workers (totals)[c]			
Full-time equivalent work years	2,900	3,060	3,060
Total recordable cases	160	170	170
Lost workday cases	77	82	82
Fatalities	0.08	0.09	0.09

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

F.2.3.1.2 *Radiological Health Impacts to Workers*

Tables F-9 and F-10 list subsurface worker health impacts from inhalation of radon-222 in the subsurface atmosphere and from ambient radiation exposure from radionuclides in the rock of the drift walls, respectively. The radiological health impacts to surface workers from inhalation of radon-222 would be small in comparison to those for subsurface workers; therefore, they were not tabulated in this appendix (see Table F-5, Footnote h, for sources of exposure).

Table F-9. Radiological health impacts to subsurface facility workers from radon exposure during construction phase.[a]

Worker group	Thermal load scenario		
	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	2,300	2,460	2,460
Maximally exposed individual (MEI) worker dose (millirem)	570	660	660
Latent cancer fatality probability for MEI	0.0002	0.0003	0.0003
Collective dose (person-rem)	260	320	320
Latent cancer fatality incidence	0.10	0.13	0.13
Noninvolved			
Full-time equivalent work years	600	600	600
Maximally exposed individual (MEI) worker dose (millirem)	430	500	500
Latent cancer fatality probability for MEI	0.0002	0.0002	0.0002
Collective dose (person-rem)	52	60	60
Latent cancer fatality incidence	0.02	0.02	0.02
All workers (totals)[c]			
Full-time equivalent work years	2,900	3,060	3,060
Collective dose (person-rem)	310	380	380
Latent cancer fatality incidence	0.12	0.15	0.15

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Table F-10. Radiological health impacts to subsurface facility workers from ambient radiation exposure during construction phase.[a]

Worker group	Thermal load scenario		
	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	2,300	2,460	2,460
Maximally exposed individual (MEI) worker dose (millirem)	200	200	200
Latent cancer fatality probability for MEI	0.00008	0.00008	0.00008
Collective dose (person-rem)	92	98	98
Latent cancer fatality incidence	0.04	0.04	0.04
Noninvolved			
Full-time equivalent work years	600	600	600
Maximally exposed individual (MEI) worker dose (millirem)	150	150	150
Latent cancer fatality probability for MEI	0.00006	0.00006	0.00006
Collective dose (person-rem)	18	18	18
Latent cancer fatality incidence	0.007	0.007	0.007
All workers (totals)[c]			
Full-time equivalent work years	2,900	3,060	3,060
Collective dose (person-rem)	110	120	120
Latent cancer fatality incidence	0.04	0.05	0.05

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

F.2.3.2 Occupational Health and Safety Impacts During the Operations Period

F.2.3.2.1 *Industrial Safety Hazards to Workers*

Tables F-11, F-12, and F-13 list estimated impacts for each worker group during waste receipt and packaging, drift development, and emplacement activities during the operations period.

Table F-11. Industrial hazard health and safety impacts to surface facility workers during waste receipt and packaging period (24 years).[a]

Worker group	Waste packaging option: Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	17,500	11,470	11,810
Total recordable cases of injury and illness	520	340	350
Lost workday cases	210	140	140
Fatalities	0.51	0.33	0.34
Noninvolved			
Full-time equivalent work years	13,150	11,620	11,760
Total recordable cases of injury and illness	430	380	390
Lost workday cases	210	190	190
Fatalities	0.38	0.34	0.34
All workers (totals)[c]			
Full-time equivalent work years	30,650	23,090	23,570
Total recordable cases of injury and illness	960	730	740
Lost workday cases	440	340	340
Fatalities	0.89	0.67	0.68

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Table F-12. Industrial hazard health and safety impacts to subsurface facility workers during drift development period.[a]

Worker group	Thermal load scenario: High (21 years)	Intermediate (21 years)	Low (22 years)
Involved			
Full-time equivalent work years[b]	6,230	6,230	6,530
Total recordable cases of injury and illness	420	420	440
Lost workday cases	300	300	310
Fatalities	0.18	0.18	0.19
Noninvolved			
Full-time equivalent work years	1,670	1,670	1,670
Total recordable cases of injury and illness	19	19	19
Lost workday cases	12	12	12
Fatalities	0.05	0.05	0.05
All workers (totals)[c]			
Full-time equivalent work years	7,900	7,900	8,210
Total recordable cases of injury and illness	440	440	460
Lost workday cases	310	310	330
Fatalities	0.23	0.23	0.24

a. Source: Impact rates from Tables F-2 and F-3.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

F.2.3.2.2 *Radiological Health Impacts to Workers*

Radiological health impacts to surface and subsurface facility workers for the operations period are the sum of the estimates of impacts to surface facility workers and subsurface facility workers during operation and monitoring (see Section F.2.3.3.2 for monitoring period).

- Table F-14 lists radiation dose to subsurface facility workers from radiation emanating from waste packages during emplacement operations.

Table F-13. Industrial hazard health and safety impacts to subsurface facility workers during emplacement period.[a]

Worker group	For all thermal load scenarios
Involved	
Full-time equivalent work years[b]	1,780
Total recordable cases of injury and illness	53
Lost workday cases	21
Fatalities	0.05
Noninvolved	
Full-time equivalent work years	380
Total recordable cases of injury and illness	13
Lost workday cases	6
Fatalities	0.01
All workers (totals)[c]	
Full-time equivalent work years	2,160
Total recordable cases of injury and illness	66
Lost workday cases	29
Fatalities	0.06

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Table F-14. Radiological health impacts to subsurface facility workers from waste packages during emplacement period (24 years).[a]

	Thermal load scenario		
Worker group	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	1,780	1,780	1,780
Dose to maximally exposed individual worker (millirem)	4,460	4,510	2,490
Latent cancer fatality probability for MEI[c]	0.002	0.002	0.001
Collective dose (person-rem)	240	240	140
Latent cancer fatality incidence	0.10	0.10	0.05
Noninvolved			
Full-time equivalent work years	380	380	380
Dose to maximally exposed individual worker (millirem)	190	190	190
Latent cancer fatality probability for MEI	0.00008	0.00008	0.00008
Collective dose (person-rem)	3	3	3
Latent cancer fatality incidence	0.001	0.001	0.001
All workers (totals)[d]			
Full-time equivalent work years	2,160	2,160	2,160
Collective dose (person-rem)	240	250	140
Latent cancer fatality incidence	0.10	0.10	0.06

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

- Table F-15 lists radiation dose to subsurface workers from the ambient radiation in the drifts during emplacement operations. Table F-16 lists radiation doses to subsurface facility workers from ambient radiation during the drift development period.

- Table F-17 lists radiation dose to subsurface workers from inhalation of airborne radon-222 in the drift atmosphere during emplacement operations. Table F-18 lists radiation dose to subsurface workers from inhalation of airborne radon-222 during drift development operations.

Table F-15. Radiological health impacts to subsurface facility workers from ambient radiation during emplacement period.[a]

Worker group	Values are independent of thermal load scenario
Involved	
Full-time equivalent work years[b]	1,780
Dose to maximally exposed individual worker (millirem)	960
Latent cancer fatality probability for MEI[c]	0.0004
Collective dose (person-rem)	71
Latent cancer fatality incidence	0.03
Noninvolved	
Full-time equivalent work years	380
Dose to maximally exposed individual worker (millirem)	480
Latent cancer fatality probability for MEI	0.0002
Collective dose (person-rem)	8
Latent cancer fatality incidence	0.003
All workers (totals)[d]	
Full-time equivalent work years	2,160
Collective dose (person-rem)	79
Latent cancer fatality incidence	0.03

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

Table F-16. Radiological health impacts to subsurface facility workers from ambient radiation during drift development period.[a]

	Thermal load scenario		
Worker group	High (21 years)	Intermediate (21 years)	Low (22 years)
Involved			
Full-time equivalent work years[b]	6,230	6,230	6,530
Dose to maximally exposed individual worker (millirem)	880	880	880
Latent cancer fatality probability for MEI[c]	0.0004	0.0004	0.0004
Collective dose (person-rem)	250	250	260
Latent cancer fatality incidence	0.10	0.10	0.10
Noninvolved			
Full-time equivalent work years	1,670	1,670	1,670
Dose to maximally exposed individual worker (millirem)	660	660	660
Latent cancer fatality probability for MEI	0.0003	0.0003	0.0003
Collective dose (person-rem)	50	50	50
Latent cancer fatality incidence	0.02	0.02	0.02
All workers (totals)[d]			
Full-time equivalent work years	7,900	7,900	8,210
Collective dose (person-rem)	300	300	310
Latent cancer fatality incidence	0.12	0.12	0.12

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

Table F-17. Radiological health impacts to subsurface facility workers from airborne radon-222 during emplacement period.[a]

Worker group	Thermal load scenario: High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	1,780	1,780	1,780
Dose to maximally exposed individual worker (millirem)	1,580	2,160	4,180
Latent cancer fatality probability for MEI[c]	0.0006	0.0008	0.002
Collective dose (person-rem)	120	160	310
Latent cancer fatality incidence	0.05	0.06	0.12
Noninvolved			
Full-time equivalent work years	380	380	380
Dose to maximally exposed individual worker (millirem)	790	1,080	2,090
Latent cancer fatality probability for MEI	0.0003	0.0004	0.0008
Collective dose (person-rem)	13	17	33
Latent cancer fatality incidence	0.005	0.007	0.01
All workers (totals)[d]			
Full-time equivalent work years	2,160	2,160	2,160
Collective dose (person-rem)	130	180	340
Latent cancer fatality incidence	0.05	0.07	0.14

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

Table F-18. Radiological health impacts to subsurface facility workers from airborne radon-222 during development period.[a]

Worker group	Thermal load scenario: High (21 years)	Intermediate (21 years)	Low (22 years)
Involved			
Full-time equivalent work years[b]	6,230	6,230	6,530
Dose to maximally exposed individual worker (millirem)	790	790	790
Latent cancer fatality probability for MEI[c]	0.0003	0.0003	0.0003
Collective dose (person-rem)	220	220	240
Latent cancer fatality incidence	0.09	0.09	0.09
Noninvolved			
Full-time equivalent work years	1,670	1,670	1,670
Dose to maximally exposed individual worker (millirem)	590	590	590
Latent cancer fatality probability for MEI	0.0002	0.0002	0.0002
Collective dose (person-rem)	45	45	45
Latent cancer fatality incidence	0.02	0.02	0.02
All workers (totals)[d]			
Full-time equivalent work years	7,900	7,900	8,210
Collective dose (person-rem)	270	270	280
Latent cancer fatality incidence	0.11	0.11	0.11

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

F.2.3.3 Occupational Health and Safety Impacts to Workers During the Monitoring Period

F.2.3.3.1 *Health and Safety Impacts to Workers from Workplace Industrial Hazards*

Health and safety impacts from industrial hazards common to the workplace for the monitoring period consist of the following:

- Impacts to surface facility workers for the 3-year surface facility decontamination period (Table F-19)
- Impacts to surface facility workers for monitoring support activities (Table F-20)
- Impacts to subsurface facility workers for monitoring and maintenance activities (Table F-21)

Table F-19. Industrial hazard health and safety impacts to surface facility workers during decontamination period.[a]

Impact	Uncanistered	Disposable canister	Dual-purpose canister
Full-time equivalent work years[b]	4,060	2,950	3,070
Total recordable cases of injury and illness	120	88	92
Lost workday cases	49	35	37
Fatalities	0.13	0.08	0.11

a. Source: Incident rate data from Table F-2.
b. Source: Table F-1.

Table F-20. Industrial hazard health and safety impacts to surface facility workers during monitoring period.[a]

Worker group	Phase	Annual
Full-time equivalent work years[b]	2,660	35
Total recordable cases of injury and illness	80	1.1
Lost workday cases	32	0.42
Fatalities	0.08	0.001

a. Source: Impacts rates from Table F-2.
b. Source: Table F-1.

Table F-21. Industrial hazard health and safety impacts for subsurface facility workers during monitoring period.[a]

	Thermal load scenario		
Worker group	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	5,240	5,240	5,780
Total recordable cases of injury and illness	160	160	170
Lost workday cases	63	63	69
Fatalities	0.15	0.15	0.17
Noninvolved			
Full-time equivalent work years	990	990	990
Total recordable cases of injury and illness	32	32	32
Lost workday cases	16	16	16
Fatalities	0.03	0.03	0.03
All workers (totals)[c]			
Full-time equivalent work years	6,230	6,230	6,760
Total recordable cases of injury and illness	190	190	210
Lost workday cases	84	84	91
Fatalities	0.18	0.18	0.20

a. Source: Impacts rates from Table F-2.
b. Source: Table F-1.
c. Totals may differ from sums due to rounding.

For surface monitoring support activities, annual impact values are listed to facilitate the extrapolation of the data for longer and shorter monitoring periods.

F.2.3.3.2 *Radiological Health Impacts to Workers*

F.2.3.3.2.1 Surface Facility Workers. During monitoring, surface workers would be involved in two types of activities—decontamination for 3 years after the completion of emplacement and support of subsurface monitoring for 76 years (starting at the end of emplacement). Surface workers providing support to the subsurface activities would receive very little radiological dose in comparison to their counterparts involved in subsurface monitoring activities. Therefore, radiological dose impacts were not included for this group; they are estimated in Appendix G, Section G.2. Radiological health impact estimates for the surface facilities decontamination activities are listed in Table F-22.

Table F-22. Radiological health impacts to surface facility workers during decontamination period.[a]

Worker group	Uncanistered	Disposable canister	Dual-purpose canister
Full-time equivalent work years[b]	4,060	2,950	3,070
Maximally exposed individual worker (millirem)[c]	300	300	300
Latent cancer fatality probability for MEI[d]	0.0001	0.0001	0.0001
Collective dose (person-rem)	290	210	220
Latent cancer fatality incidence	0.11	0.08	0.09

a. Source: Dose rate data from Table F-5.
b. Source: Table F-1.
c. Source: Based on Table F-4, maximum dose of 100 millirem per year for 3 years.
d. MEI = maximally exposed individual.

F.2.3.3.2.2 Subsurface Facility Workers. Radiological health impacts to subsurface facility workers during monitoring are listed in Table F-23. Maximum worker dose values in the table were based on a maximum work period of 50 years on a monitoring assignment rather than a 76-year monitoring period.

Table F-23. Radiological health impacts to subsurface facility workers during a 50-year work period during a 76-year monitoring period.[a]

	Thermal load scenario		
Worker group	High	Intermediate	Low
Involved			
Full-time equivalent work years[b]	5,240	5,240	5,780
Dose to maximally exposed individual worker (millirem)	16,240	18,940	17,610
Latent cancer fatality probability for MEI[c]	0.006	0.008	0.007
Collective dose (person-rem)	1,760	2,050	2,060
Latent cancer fatality incidence	0.71	0.82	0.83
Noninvolved			
Full-time equivalent work years	990	990	990
Dose to maximally exposed individual worker (millirem)	6,200	7,550	8,000
Latent cancer fatality probability for MEI	0.003	0.003	0.003
Collective dose (person-rem)	120	150	160
Latent cancer fatality incidence	0.05	0.06	0.06
All workers (totals)[d]			
Full-time equivalent work years	6,230	6,230	6,760
Collective dose (person-rem)	1,880	2,200	2,220
Latent cancer fatality incidence	0.75	0.88	0.89

a. Source: Exposure data from Table F-4.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

In addition, DOE considered monitoring periods as short as 26 years and as long as 276 years. Radiological health impacts for both of these monitoring periods were evaluated; the radiological health impact estimates are listed in Table F-24. Doses to the maximally exposed worker were based on a 50-year employment period rather than the 276-year monitoring period.

Table F-24. Radiological health impacts to workers during a 26-year and a 276-year monitoring period, dual-purpose canister packaging scenario.[a]

Group	26 years			276 years		
	High thermal load	Intermediate thermal load	Low thermal load	High thermal load	Intermediate thermal load	Low thermal load
Involved						
Full-time equivalent work years	1,790	1,790	1,980	19,040	19,040	20,980
Dose to maximally exposed individual worker (millirem)	8,440	9,850	9,160	16,240	18,940	17,610
Latent cancer fatality probability for MEI[b]	0.003	0.004	0.004	0.006	0.008	0.007
Collective dose (person-rem)	600	700	710	6,400	7,430	7,500
Latent cancer fatality incidence	0.24	0.28	0.28	2.6	3.0	3.0
Noninvolved						
Full-time equivalent work years	340	340	340	3,590	3,590	3,590
Dose to maximally exposed individual worker (millirem)	3,220	3,930	4,160	6,200	7,550	8,000
Latent cancer fatality probability for MEI	0.001	0.002	0.002	0.002	0.003	0.003
Collective dose (person-rem)	42	51	54	450	540	570
Latent cancer fatality incidence	0.02	0.02	0.02	0.18	0.22	0.23
All workers (totals)						
Full-time equivalent work years	2,130	2,130	2,320	22,630	22,630	24,570
Collective dose (person-rem)	640	750	760	6,850	7,970	8,073
Latent cancer fatality incidence	0.26	0.30	0.30	2.7	3.2	3.2

a. Sources: Tables F-1, F-4, and F-23.
b. MEI = maximally exposed individual.

F.2.3.4 Occupational Health and Safety Impacts During the Closure Phase

F.2.3.4.1 *Health and Safety Impacts to Workers from Workplace Industrial Hazards*

Health and safety impacts to workers from industrial hazards common to the workplace for closure are listed in Table F-25 for surface facility workers and Table F-26 for subsurface facility workers.

F.2.3.4.2 *Radiological Health Impacts to Workers*

Radiological health impact to workers from closure activities are the sum of the following components:

- Radiological health impacts to subsurface workers from radiation emanating from the waste packages during the closure phase (Table F-27)
- Radiological impacts to subsurface workers from the ambient radiation field in the drifts during the closure phase (Table F-28)
- Radiological impacts to subsurface workers from inhalation of radon-222 in the drift atmosphere during the closure phase (Table F-29)

Table F-25. Industrial hazard health and safety impacts to surface facility workers during closure phase.[a]

Worker group	Waste packaging option		
	Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	1,580	1,110	1,200
Total recordable cases of injury and illness	97	68	73
Lost workday cases	46	33	35
Fatalities	0.04	0.03	0.03
Noninvolved			
Full-time equivalent work years	600	420	460
Total recordable cases of injury and illness	20	14	15
Lost workday cases	10	7	7
Fatalities	0.02	0.01	0.01
All workers (totals)[c]			
Full-time equivalent work years	2,180	1,540	1,650
Total recordable cases of injury and illness	120	82	88
Lost workday cases	56	40	43
Fatalities	0.06	0.04	0.04

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Table F-26. Industrial hazard health and safety impacts to subsurface facility workers during closure phase.[a]

Worker group	Thermal load scenario		
	High (6 years)	Intermediate (6 years)	Low (15 years)
Involved			
Full-time equivalent work years[b]	1,310	1,310	3,270
Total recordable cases of injury and illness	80	80	200
Lost workday cases	39	39	96
Fatalities	0.04	0.04	0.09
Noninvolved			
Full-time equivalent work years	260	260	660
Total recordable cases of injury and illness	9	9	22
Lost workday cases	4	4	11
Fatalities	0.01	0.01	0.02
All workers (totals)[c]			
Full-time equivalent work years	1,570	1,570	3,930
Total recordable cases of injury and illness	89	89	220
Lost workday cases	43	43	110
Fatalities	0.05	0.05	0.11

a. Source: Impact rates from Table F-2.
b. Source: Table F-1.
c. Totals might differ from sums due to rounding.

Because the surface facilities would be largely decontaminated at the beginning of the monitoring period (the exception would be a small facility retained to handle an operations emergency), radiological health impacts to surface facility workers during closure would be small in comparison to those to the subsurface facility workers and so are not included here.

Table F-27. Radiological health impacts to subsurface facility workers from waste package radiation exposures during closure phase.[a]

Worker group	Thermal load scenario: High (5 years)	Intermediate (6 years)	Low (15 years)
Involved			
Full-time equivalent work years[b]	1,310	1,310	3,270
Dose to maximally exposed individual worker (millirem)	650	650	960
Latent cancer fatality probability for MEI[c]	0.0003	0.0003	0.0004
Collective dose (person-rem)	75	75	110
Latent cancer fatality incidence	0.03	0.03	0.04
Noninvolved			
Full-time equivalent work years	260	260	660
Dose to maximally exposed individual worker (millirem)	48	48	120
Latent cancer fatality probability for MEI	0.00002	0.00002	0.00005
Collective dose (person-rem)	2	2	5
Latent cancer fatality incidence	0.0008	0.0008	0.002
All workers (totals)[d]			
Full-time equivalent work years	1,570	1,570	3,930
Collective dose (person-rem)	77	77	115
Latent cancer fatality incidence	0.03	0.03	0.05

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

Table F-28. Radiological health impacts to subsurface facility workers from ambient radiation exposures during closure phase.[a]

Worker group	Thermal load scenario: High (5 years)	Intermediate (6 years)	Low (15 years)
Involved			
Full-time equivalent work years[b]	1,310	1,310	3,270
Dose to maximally exposed individual worker (millirem)	240	240	600
Latent cancer fatality probability for MEI[c]	0.0001	0.0001	0.0002
Collective dose (person-rem)	52	52	130
Latent cancer fatality incidence	0.02	0.02	0.05
Noninvolved			
Full-time equivalent work years	260	260	660
Dose to maximally exposed individual worker (millirem)	180	180	450
Latent cancer fatality probability for MEI	0.00006	0.00007	0.00018
Collective dose (person-rem)	8	8	20
Latent cancer fatality incidence	0.003	0.003	0.008
All workers (totals)[d]			
Full-time equivalent work years	1,570	1,570	3,930
Collective dose (person-rem)	60	60	150
Latent cancer fatality incidence	0.02	0.02	0.06

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

Table F-29. Radiological health impacts to subsurface facility workers from radon-222 exposure during closure phase.[a]

Worker group	Thermal load scenario: High (5 years)	Intermediate (6 years)	Low (15 years)
Involved			
Full-time equivalent work years[b]	1,310	1,310	3,270
Dose to maximally exposed individual worker (millirem)	1,150	1,480	3,960
Latent cancer fatality probability for MEI[c]	0.0005	0.0006	0.002
Collective dose (person-rem)	250	320	860
Latent cancer fatality incidence	0.10	0.13	0.35
Noninvolved			
Full-time equivalent work years	260	260	660
Dose to maximally exposed individual worker (millirem)	860	1,110	2,970
Latent cancer fatality probability for MEI	0.0003	0.0004	0.001
Collective dose (person-rem)	38	49	130
Latent cancer fatality incidence	0.02	0.02	0.05
All workers (totals)[d]			
Full-time equivalent work years	1,570	1,570	3,930
Collective dose (person-rem)	290	370	990
Latent cancer fatality incidence	0.12	0.15	0.40

a. Source: Exposure data from Table F-5.
b. Source: Table F-1.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

F.3 Human Health and Safety Impact Analysis for Inventory Modules 1 and 2

DOE performed an analysis to estimate the occupational and public health and safety impacts from the emplacement of Inventory Module 1 or 2. Module 1 would involve the emplacement of additional spent nuclear fuel and high-level radioactive waste in the repository; Inventory Module 2 would emplace commercial Greater-Than-Class-C waste and DOE Special-Performance-Assessment-Required waste, which is equivalent to commercial Greater-Than-Class-C waste, in addition to the inventory from Module 1. The volumes of Greater-Than-Class-C and Special-Performance-Assessment-Required waste would be less than that for spent nuclear fuel and high-level radioactive waste (TRW 1999c, Table 3.1). Waste packages containing these materials would be placed between the waste packages containing spent nuclear fuel and high-level radioactive waste (see Chapter 8, Section 8.1.2.1).

With regard to estimating heath and safety impacts for the inventory modules, the characteristics of the spent nuclear fuel and high-level radioactive waste were taken to be the same as those for the Proposed Action, but there would be more material to emplace (see Appendix A, Section A.2). As described in Appendix A, the radiological content of the Greater-Than-Class-C waste and Special-Performance-Assessment-Required waste, which is the additional material in Module 2, is much less than that for spent nuclear fuel and high-level radioactive waste. Therefore, the emplacement of the Module 2 material would not meaningfully increase radiological impacts to workers over those estimated for the Module 1 inventory. Further, the facility design parameters, on which the impact estimates are based, are extrapolations from existing designs and have some uncertainty associated with them [see, for example, TRW (1999c), Section 6.2, first paragraph]. Therefore, separate occupational and public health and safety impact analyses were not performed for Module 2 because the impacts for Inventory Modules 1 and 2 would not differ meaningfully.

The calculation of health and safety impacts to workers assumed that the throughput rate of materials for the facility would remain the same as that assumed for the Proposed Action during repository operations (that is, the 70,000-MTHM case). In addition, for the inventory modules the period of operations would be extended to accommodate the additional materials, and the monitoring period would be reduced such that the Yucca Mountain repository operations and monitoring activities would still occur in a 100-year period. Table F-30 summarizes the expected lengths of the phases for Yucca Mountain Repository activities for the inventory modules. These periods were used in the occupational and public health and safety impact calculations.

Table F-30. Expected durations (years) of the Proposed Action and Inventory Modules 1 and 2.[a]

Inventory	Construction phase (2005-2010)	Operation and monitoring phase (2010-2110)				Closure phase (starts in 2110)
		Development[b]	Emplacement	Monitoring	Total	
Proposed Action	5	22	24	76	100[c]	6-15[d]
Module 1 or 2	5	36	38	62	100	13-27[e]

a. Sources: TRW (1999b, all); TRW (1999c, all); Jessen (1999, all).
b. Continuing subsurface construction (development) activities are concurrent with emplacement activities.
c. Closure is assumed to begin 100 years following initial emplacement for the Proposed Action and Module 1 or 2 for the evaluation of cumulative impacts.
d. 6, 6, and 15 years for the high, intermediate, and low thermal load scenarios, respectively.
e. 13, 17, and 27 years for the high, intermediate, and low thermal load scenarios, respectively.

This section discusses the methodologies and data used to estimate occupational radiological health and safety impacts resulting from construction, operation and monitoring, and closure of the Yucca Mountain Repository for Inventory Modules 1 and 2, and presents the detailed results. Section F.3.1 describes the methods DOE used to estimate impacts. Section F.3.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources. Section F.3.3 contains detailed tabulations of results.

F.3.1 METHODOLOGY FOR CALCULATING HUMAN HEALTH AND SAFETY IMPACTS

DOE used the methodology described in Section F.2.1 to estimate health and safety impacts for the inventory modules. This methodology involved assembling data for the number of full-time equivalent workers for each repository phase. These numbers were used with statistics for the likelihood of an impact (industrial hazards) or the expected dose rate in the worker environment to calculate health and safety impacts. The way in which the input data was combined in the calculation of health and safety impacts is described in more detail in Section F.2.1. Some of the input data for the calculations for the inventory modules are different from those for the Proposed Action, as discussed in the next section.

F.3.2 DATA SOURCES AND TABULATIONS

F.3.2.1 Full-Time Equivalent Worker-Year Estimates for the Repository Phases for Inventory Modules 1 and 2

The full-time equivalent work-year estimates for the inventory modules are different from those for the Proposed Action. Table F-31 lists the number of full-time equivalent work years for the various repository phases for the inventory modules. Each full-time equivalent work year represents 2,000 work hours, the hours assumed to be worked in a normal work year.

This analysis divides the repository workforce into two groups—involved and noninvolved workers (see Section F.2 for definitions of involved and noninvolved workers). It did not consider workers whose place of employment would be other than at the repository site.

Table F-31. Full-time equivalent work years for various repository periods for Inventory Modules 1 and 2.

			High thermal load			Intermediate thermal load			Low thermal load		
Phase	Period	Sources[a]	UC[b]	DISP[c]	DPC[d]	UC	DISP	DPC	UC	DISP	DPC
Construction											
Surface	44 months	(1)									
Involved worker			2,380	1,650	1,760	2,380	1,650	1,760	2,380	1,650	1,760
Noninvolved worker			900	630	670	900	630	670	900	670	680
Subsurface	5 years	(2)									
Involved worker			2,460	2,460	2,460	2,460	2,460	2,460	2,460	2,460	2,460
Noninvolved worker			600	600	600	600	600	600	600	600	600
Subtotal			*6,340*	*5,340*	*5,480*	*6,340*	*5,340*	*5,480*	*6,340*	*5,380*	*5,480*
Operation and monitoring											
Operation											
Subsurface drift development	36 years	(5)									
Involved worker			9,110	9,110	9,110	9,540	9,540	9,540	10,370	10,370	10,370
Noninvolved worker			2,450	2,450	2,450	2,450	2,450	2,450	2,740	2,740	2,740
Subsurface emplacement	38 years	(4)									
Involved worker			2,810	2,810	2,810	2,810	2,810	2,810	3,000	3,000	3,000
Noninvolved worker			610	610	610	610	610	610	650	650	650
Surface handling	38 years	(3)									
Involved worker			27,700	18,160	18,700	27,700	18,160	18,700	27,700	18,160	18,700
Noninvolved worker			20,820	18,390	18,620	20,820	18,390	18,620	20,820	18,390	18,620
Subtotal operation			*63,500*	*51,530*	*52,290*	*63,930*	*51,960*	*52,720*	*65,270*	*53,310*	*54,070*
Monitoring											
Surface support	62 years	(6)									
Involved worker			2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170	2,170
Noninvolved worker			NA[e]	NA	NA	NA	NA	NA	NA	NA	NA
Surface facility decontamination	3 years	(7)									
Involved worker			4,060	2,950	3,070	4,060	2,950	3,070	4,060	2,950	3,070
Noninvolved worker			NA	NA	NA	NA	NA	NA	NA	NA	NA
Subsurface monitoring	62 years	(8)									
Involved worker			4,280	4,280	4,280	4,710	4,710	4,710	5,950	5,950	5,950
Noninvolved worker			810	810	810	810	810	810	1,610	1,610	1,610
Subtotal monitoring			*11,320*	*10,200*	*10,320*	*11,750*	*10,640*	*10,760*	*13,800*	*12,680*	*12,800*
Subtotal operation and monitoring			*74,820*	*61,730*	*62,610*	*75,680*	*62,600*	*63,480*	*79,070*	*65,990*	*66,870*
Closure											
Surface	6 years	(9)									
Involved worker			1,580	1,110	1,200	1,580	1,110	1,200	1,580	1,110	1,200
Noninvolved worker			600	420	460	600	420	460	600	420	460
Subsurface	(f)	(10)									
Involved worker			2,830	2,830	2,830	3,710	3,710	3,710	5,890	5,890	5,890
Noninvolved worker			570	570	570	750	750	750	1,190	1,190	1,190
Subtotal closure			*5,580*	*4,940*	*5,060*	*6,630*	*5,940*	*6,100*	*9,250*	*8,610*	*8,720*
Totals[d]			***86,740***	***72,020***	***73,150***	***88,660***	***73,930***	***75,070***	***94,670***	***79,980***	***81,080***

a. Sources: (1) TRW (1999c, Table 6-1); (2) TRW (1999b, Table 6.2.1.1-1); (3) TRW (1999c, Table 6-2; (4) TRW (1999b, Table 6.2.3.1-1); (5) TRW (1999b, Table 6.2.3.1-1); (6) TRW (1999c, Table 6-5); (7) TRW (1999c, Table 6-4); (8) TRW (1999b, Table 6.2.4.1-1); (9) TRW (1999c, Table 6-6); (10) TRW (1999b, Table 6.2.6.1-1).

b. UC = uncanistered packaging scenario.

c. DISP = disposable canister packaging scenario.

d. DPC = dual-purpose canister packaging scenario.

e. NA = not applicable, all workers assumed to be involved.

f. High thermal load, 13 years; intermediate thermal load, 17 years; low thermal load, 27 years.

g. Totals might differ from sums due to rounding.

F.3.2.2 Statistics on Health and Safety Impacts from Industrial Hazards in the Workplace

DOE used the same statistics for health and safety impacts from industrial hazards common to the workplace that were used for the Proposed Action (70,000 MTHM) for analyzing the inventory module impacts (see Table F-2).

F.3.2.3 Estimates of Radiological Exposure Rates and Times for Inventory Modules 1 and 2

DOE used the values in Table F-5 (Proposed Action) for exposure rates, occupancy times, and the fraction of the workforce that would be exposed to estimate radiological health impacts for the inventory module cases, except for doses from the waste packages and from radon-222 inhalation for the subsurface emplacement, monitoring, and closure phases. Annual exposures to subsurface workers for Inventory Modules 1 and 2 from radiation emanating from the waste packages are listed as part of Table F-6. Table F-32 lists annual dose rates from inhalation of radon-222 and its decay products. Section F.1.1.6 discusses the basis for the values in Table F-32.

Table F-32. Correction factors and annual exposures from radon-222 and its decay products for the project phases or periods for Inventory Modules 1 and 2.[a]

	Correction factor			Annual dose rate (millirem per year)		
Subsurface project period	High	Intermediate	Low	High	Intermediate	Low
Construction	2.1	2.1	2.1	126	126	126
Drift development	0.6	0.6	0.6	36	36	36
Emplacement	2.0	1.7	3.5	120	120	210
Monitoring	4.2	2.7	4.1	252	160	246
Closure	4.2	2.7	4.1	252	160	246

a. Based on measured value of 60 millirem per year corrected for repository volume and ventilation rate; see the discussions in Section F.1.1.6 and Appendix G (Section G.2.3.1).

F.3.3 DETAILED HUMAN HEALTH AND SAFETY IMPACTS TO WORKERS – INVENTORY MODULES 1 AND 2

F.3.3.1 Construction Phase

F.3.3.1.1 *Industrial Hazards to Workers*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the construction phase. Impact values for surface workers are the same as those presented for the Proposed Action in Table F-7. Impact values for subsurface workers are presented in Table F-33. The subsurface impacts are independent of thermal load or packaging scenarios.

F.3.3.1.2 *Radiological Health Impacts to Workers*

Table F-34 lists subsurface worker health impacts from inhalation of radon-222 and its decay products in the subsurface atmosphere and from exposure to natural radiation from radionuclides in the drift walls. The radiological health impacts to surface workers from inhalation of radon-222 and its decay products would be small in comparison to those for subsurface workers; therefore, they are not tabulated here (see Table F-5, Footnote h).

Table F-33. Industrial hazard health and safety impacts to subsurface facility workers during construction phase – Inventory Module 1 or 2.[a]

Worker group	Impacts
Involved	
Full-time equivalent work years[b]	2,460
Total recordable cases of injury and illness	150
Lost workday cases	72
Fatalities	0.07
Noninvolved	
Full-time equivalent work years	600
Total recordable cases of injury and illness	20
Lost workday cases	10
Fatalities	0.02
All workers (totals)[c]	
Full-time equivalent work years	3,060
Total recordable cases of injury and illness	170
Lost workday cases	82
Fatalities	0.09

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-34. Radiological health impacts to subsurface facility workers from radon inhalation and natural exposure for the construction phase – Inventory Modules 1 and 2.[a]

Worker group	Radon inhalation exposure	Subsurface ambient exposure
Involved		
Full-time equivalent work years[c]	2,460	2,460
Dose to maximally exposed individual worker (millirem)	630	200
Latent cancer fatality probability for MEI[c]	0.0002	0.00008
Collective dose (person-rem)	310	98
Latent cancer fatality incidence	0.12	0.04
Noninvolved		
Full-time equivalent work years	600	600
Dose to maximally exposed individual worker (millirem)	470	150
Latent cancer fatality probability for MEI	0.0002	0.00006
Collective dose (person-rem)	57	18
Latent cancer fatality incidence	0.02	0.007
All workers (totals)[d]		
Full-time equivalent work years	3,060	3,060
Collective dose (person-rem)	370	120
Latent cancer fatality incidence	0.15	0.05

a. Sources: Table F-5 (ambient exposure); Table F-32 (exposure from radon inhalation).
b. Source: Table F-31.
c. MEI = maximally exposed individual.
d. Totals might differ from sums due to rounding.

F.3.3.2 Operation and Monitoring Phase

F.3.3.2.1 *Health and Safety Impacts to Workers from Industrial Hazards*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the operation and monitoring phase. These impacts would consist of four components:

- Health and safety impacts to surface workers for operations (Table F-35)
- Health and safety impacts to subsurface workers for emplacement and for drift development (Table F-36)
- Health and safety impacts to subsurface workers for the monitoring period (Table F-37)
- Health and safety impacts to surface workers for surface facility decontamination and monitoring support (Table F-38)

Table F-35. Industrial hazard health and safety impacts for surface facility workers during a 38-year operations period by packaging option – Inventory Module 1 or 2.[a]

Worker group	Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	27,700	18,160	18,700
Total recordable cases of injury and illness	830	540	560
Lost workday cases	360	240	240
Fatalities	0.80	0.53	0.55
Noninvolved			
Full-time equivalent work years	20,820	18,390	18,620
Total recordable cases of injury and illness	680	600	610
Lost workday cases	340	300	300
Fatalities	0.60	0.53	0.54
All workers (totals)[c]			
Full-time equivalent work years	48,530	36,560	37,320
Total recordable cases of injury and illness	1,520	1,150	1,170
Lost workday cases	700	530	540
Fatalities	1.4	1.1	1.1

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

F.3.3.2.2 *Radiological Health Impacts to Workers*

This section details radiological health impacts to workers during the operation and monitoring phase for the inventory modules. These impacts consist of four components:

- Radiological health impacts to surface workers during operations (Table F-39)
- Radiological health impacts to subsurface workers during operations (emplacement and drift development) (Table F-40)
- Radiological health impacts to workers during surface facility decontamination and monitoring support (Table F-41)
- Radiological health impacts to subsurface workers for the monitoring period (Table F-42)

Table F-36. Industrial hazard health and safety impacts for subsurface facility workers for development and emplacement period – Inventory Module 1 or 2.[a]

Worker group	High thermal load	Intermediate thermal load	Low thermal load
Involved			
Full-time equivalent work years[b]	11,920	12,350	13,370
Total recordable cases of injury and illness	700	730	790
Lost workday cases	480	500	540
Fatalities	0.35	0.36	0.39
Noninvolved			
Full-time equivalent work years	3,060	3,060	3,380
Total recordable cases of injury and illness	48	48	52
Lost workday cases	27	27	29
Fatalities	0.09	0.09	0.10
All workers (totals)[c]			
Full-time equivalent work years	14,980	15,410	16,750
Total recordable cases of injury and illness	750	780	850
Lost workday cases	500	530	570
Fatalities	0.42	0.45	0.49

a. Source: Impact rates from Tables F-2 and F-3.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-37. Industrial hazard health and safety impacts for subsurface facility workers during monitoring period – Inventory Module 1 or 2.[a]

Worker group	High thermal load	Intermediate thermal load	Low thermal load
Involved			
Full-time equivalent work years[b]	4,280	4,710	5,950
Total recordable cases of injury and illness	130	140	180
Lost workday cases	55	61	77
Fatalities	0.12	0.14	0.17
Noninvolved			
Full-time equivalent work years	810	810	1610
Total recordable cases of injury and illness	26	26	53
Lost workday cases	13	13	26
Fatalities	0.02	0.02	0.05
All workers (totals)[c]			
Full-time equivalent work years	5,080	5,520	7,560
Total recordable cases of injury and illness	160	170	230
Lost workday cases	68	74	100
Fatalities	0.15	0.16	0.22

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-38. Industrial hazard health and safety impacts by packaging option to workers during surface facility decontamination and monitoring period – Inventory Module 1 or 2.[a]

Involved workers	Uncanistered	Disposable canister	Dual-purpose canister
Full-time equivalent work years[b]	6,230	5,120	5,240
Total recordable cases of injury and illness	190	150	160
Lost workday cases	80	70	70
Fatalities	0.18	0.15	0.15

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.

Table F-39. Radiological health impacts to surface facility workers for a 38-year operations period – Inventory Module 1 or 2.[a]

Worker group	Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	27,700	18,160	18,700
Dose to maximally exposed individual worker (millirem)	15,200	15,200	15,200
Latent cancer fatality probability for maximally exposed individual	0.006	0.006	0.006
Collective dose (person-rem)	8,180	3,890	3,950
Latent cancer fatality incidence	3.3	1.6	1.6
Noninvolved			
Full-time equivalent work years	20,820	18,390	18,620
Dose to maximally exposed individual worker (millirem)	950	950	950
Latent cancer fatality probability for maximally exposed individual	0.0004	0.0004	0.0004
Collective dose (person-rem)	170	140	140
Latent cancer fatality incidence	0.07	0.06	0.06
All workers (totals)[c]			
Full-time equivalent work years	48,530	36,560	37,320
Collective dose (person-rem)	8,350	4,030	4,090
Latent cancer fatality incidence	3.3	1.6	1.6

a. Source: Exposure data from Table F-5.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-40. Radiological health impacts to subsurface workers for emplacement and drift development during operations period – Inventory Module 1 or 2.[a]

Worker group	High thermal load	Intermediate thermal load	Low thermal load
Involved			
Full-time equivalent work years[b]	11,900	12,350	13,370
Dose to maximally exposed individual worker (millirem)	13,220	12,530	13,460
Latent cancer fatality probability for maximally exposed individual	0.005	0.005	0.005
Collective dose (person-rem)	1,530	1,510	1,770
Latent cancer fatality incidence	0.61	0.60	0.71
Noninvolved			
Full-time equivalent work years	3,060	3,060	3,380
Dose to maximally exposed individual worker (millirem)	2,280	2,240	4,290
Latent cancer fatality probability for maximally exposed individual	0.0009	0.0009	0.002
Collective dose (person-rem)	190	190	240
Latent cancer fatality incidence	0.08	0.08	0.10
All workers (totals)[c]			
Full-time equivalent work years	14,980	15,410	16,750
Collective dose (person-rem)	1,720	1,700	2,010
Latent cancer fatality incidence	0.69	0.68	0.80

a. Source: Exposure data from Table F-4 except waste package exposures, which are from Table F-6.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-41. Radiological health impacts to surface facility workers for decontamination and monitoring support – Inventory Module 1 or 2.[a]

Involved workers	Uncanistered	Disposable canister	Dual-purpose canister
Full-time equivalent work years[b]	6,230	5,120	5,240
Dose to maximally exposed individual worker (millirem)	300	300	300
Latent cancer fatality probability for maximally exposed individual	0.0001	0.0001	0.0001
Collective dose (person-rem)	290	210	220
Latent cancer fatality incidence	0.11	0.08	0.09

a. Source: Exposure data from Table F-4.
b. Source: Table F-31.

Table F-42. Radiological health impacts to subsurface facility workers for a 62-year monitoring period – Inventory Module 1 or 2.[a]

Worker group	High thermal load	Intermediate thermal load	Low thermal load
Involved			
Full-time equivalent work years[b]	4,280	4,710	5,950
Dose to maximally exposed individual worker (millirem)	19,240	14,740	16,710
Latent cancer fatality probability for maximally exposed individual	0.008	0.006	0.007
Collective dose (person-rem)	1,700	1,440	2,050
Latent cancer fatality incidence	0.68	0.58	0.82
Noninvolved			
Full-time equivalent work years	810	810	1,610
Dose to maximally exposed individual worker (millirem)	7,700	5,450	7,550
Latent cancer fatality probability for maximally exposed individual	0.003	0.002	0.003
Collective dose (person-rem)	120	88	240
Latent cancer fatality incidence	0.05	0.04	0.10
All workers (totals)[c]			
Full-time equivalent work years	5,080	5,520	7,560
Collective dose (person-rem)	2,300	2,050	2,470
Latent cancer fatality incidence	0.92	0.82	3.0

a. Source: Exposure data from Table F-5 except for exposure from waste packages, which is from Table F-6.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

F.3.3.3 Closure Phase

F.3.3.3.1 *Health and Safety Impacts to Workers from Industrial Hazards*

This section details health and safety impacts to workers from industrial hazards common to the workplace for the closure phase. The impacts would consist of two components—impacts to surface workers supporting the closure operations, and impacts to subsurface workers during the closure phase. These impacts are listed in Tables F-43 and F-44, respectively.

Table F-43. Industrial hazard health and safety impacts to surface workers during the closure phase – Inventory Module 1 or 2.[a]

Worker group	Uncanistered	Disposable canister	Dual-purpose canister
Involved			
Full-time equivalent work years[b]	1,580	1,110	1,200
Total recordable cases of injury and illness	97	68	73
Lost workday cases	46	33	35
Fatalities	0.05	0.03	0.04
Noninvolved			
Full-time equivalent work years	600	420	460
Total recordable cases of injury and illness	20	14	15
Lost workday cases	10	7	7
Fatalities	0.02	0.01	0.01
All workers (totals)[c]			
Full-time equivalent work years	2,180	1,540	1,650
Total recordable cases of injury and illness	116	82	88
Lost workday cases	56	40	43
Fatalities	0.06	0.04	0.05

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

Table F-44. Health and safety impacts to subsurface facility workers from industrial hazards during the closure phase – Inventory Module 1 or 2.[a]

Worker group	High thermal load	Intermediate thermal load	Low thermal load
Involved			
Full-time equivalent work years[b]	2,830	3,710	5,890
Total recordable cases of injury and illness	170	230	360
Lost workday cases	84	110	170
Fatalities	0.08	0.11	0.17
Noninvolved			
Full-time equivalent work years	570	750	1,190
Total recordable cases of injury and illness	19	25	39
Lost workday cases	9	12	19
Fatalities	0.02	0.02	0.03
All workers (totals)[c]			
Full-time equivalent work years	3,410	4,450	7,070
Total recordable cases of injury and illness	193	250	400
Lost workday cases	93	120	190
Fatalities	0.10	0.13	0.21

a. Source: Impact rates from Table F-2.
b. Source: Table F-31.
c. Totals might differ from sums due to rounding.

F.4 Human Health and Safety Impact Analysis for the Retrieval Contingency

Nuclear Regulatory Commission regulations state that the period for which DOE must maintain the ability to retrieve waste is at least 50 years after the start of emplacement operations [10 CFR 60.111(b)]. Although DOE does not anticipate retrieval and it is not part of the Proposed Action, the Department would maintain the ability to retrieve the waste for at least 100 years and possibly for as long as 300 years after the start of emplacement. Factors that could lead to a decision to retrieve the waste would be (1) to protect the public health and safety or the environment or (2) to recover resources from spent nuclear fuel. This EIS evaluates retrieval as a contingency action and describes potential impacts should it occur. The analysis assumes that under this contingency DOE would retrieve all the waste associated with the Proposed Action and would place it on surface storage pads pending future decisions about its ultimate disposition.

The analysis of health and safety impacts to workers divided the retrieval period into two subperiods, as follows:

- First, a construction subperiod in which DOE would (1) build the surface facilities necessary to handle and enclose retrieved waste packages in concrete storage units in preparation for placement on concrete storage pads, and (2) construct the concrete storage pads.

  No radioactive materials would be involved in the construction subperiod, so health and safety impacts would be limited to those associated with industrial hazards in the workplace. DOE expects this subperiod would last 2 to 3 years, although construction of the concrete storage pads probably would continue on an as-needed basis during most of the operations subperiod. The analysis assumed a 3-year period.

- Second, an operations subperiod during which the waste packages would be retrieved and moved to the Waste Retrieval Transfer Building. Surface facility workers would unload the waste package from the transfer vehicle and place it on a concrete base. The package and concrete base would then be enclosed in a concrete storage unit that would be placed on the concrete storage pad. The analysis assumed an 11-year period.

This section discusses the methodologies and data used to estimate human health and safety impacts resulting from the retrieval contingency. Section F.4.1 describes the methods DOE used to estimate impacts. Section F.4.2 contains tabulations of the detailed data used in the impact calculations and references to the data sources. Section F.4.3 contains detailed tabulations of the results.

F.4.1 METHODOLOGY FOR CALCULATING HUMAN HEALTH AND SAFETY IMPACTS

DOE used the methodology summarized in Section F.2.1 to estimate health and safety impacts for the retrieval contingency. This involved assembling data for the number of full-time equivalent workers for each retrieval activity. These numbers were used with statistics on the likelihood of an impact (industrial hazards), or the estimated radiological dose rate in the worker environment, to calculate health and safety impacts. The way in which the input data were combined to calculate health and safety impacts is described in more detail in Section F.2.1. Some of the input data in the retrieval impact calculations are different from those for the Proposed Action, as described in the next section.

F.4.2 DATA SOURCES AND TABULATIONS

F.4.2.1 Full-Time Equivalent Work-Year Estimates for the Retrieval Contingency

This analysis divides the repository workforce into two groups—involved and noninvolved workers (see Section F.2 for definitions of involved and noninvolved workers).

Table F-45 lists the number of workers involved in the two subperiods of the retrieval operation and the sources of the numbers. They are tabulated as full-time equivalent work years. Each full-time equivalent

Table F-45. Full-time equivalent work-year estimates for retrieval.

Subperiod and worker group	Length of subperiod (years)	Full-time equivalent work years
Surface facilities, construction[a]	3	
Involved		1,130
Noninvolved		430
Surface facilities, retrieval support[b]	11	
Involved		320
Noninvolved		870
Subsurface facility retrieval operations[c]	11	
Involved		810
Noninvolved		180
Total		***3,740***

a. Source: TRW (1999c, Table I-2).
b. Source: TRW (1999c, Table I-3).
c. Source: TRW (1999b, Table 6.1.5.1-1).

work year represents 2,000 work hours, the hours assumed to be worked in a normal work year. The full-time equivalent work year estimates are independent of thermal load.

F.4.2.2 Statistics on Health and Safety Impacts from Industrial Hazards in the Workplace

For the retrieval contingency, DOE used the same set of statistics on health and safety impacts from industrial hazards common to the workplace that were used for the Proposed Action (70,000 MTHM) (see Table F-2). The specific statistics that were applied to the retrieval contingency subphases are listed in Table F-46.

Table F-46. Statistics for industrial hazard impacts for retrieval.

Subperiod and worker group	Total recordable incidents (rate per 100 FTEs)[a]	Lost workday cases (rate per 100 FTEs)	Fatalities (rate per 100,000 FTEs)[b]
Construction, surface workers[c]			2.9
Involved	6.1	2.9	
Noninvolved	3.3	1.6	
Retrieval, surface workers[d]			2.9
Involved	3.0	1.2	
Noninvolved	3.3	1.6	
Retrieval, subsurface workers[d]			2.9
Involved	3.0	1.2	
Noninvolved	3.3	1.6	

a. FTE = full-time equivalent work years.
b. Source: Data Set 4, Section F.2.2.
c. Source: Data Set 1, Section F.2.2.
d. Source: Data Set 3, Section F.2.2.

F.4.2.3 Estimated Radiological Exposure Rates and Times for the Retrieval Contingency

DOE used the same set of worker exposure rates and exposure times as those used for evaluating radiological worker impacts for the Proposed Action. Table F-47 presents the specific application of this data to the retrieval contingency subphases. The source of the information is also referenced. The rates used in the analysis did not take into account radioactive decay for the period between emplacement and retrieval.

Table F-47. Radiological doses and exposure data used to calculate worker exposures during retrieval.[a]

Subperiod and worker group	Source of exposure	Occupancy factor for exposure rate (fraction of 8-hour workday)	Annual dose (millirem, except where noted)	Full-time equivalent workers[b]	Source[c]
Construction					
Surface					
Involved	None				
Noninvolved	None				
Operations					
Surface					
Involved	Waste package	1.0	400	13	(1)
	Radiation		100	16	(1)
Noninvolved		1.0	25	22	(2)
			0	57	(2)
Subsurface					
Involved	Waste package	1.0	Variable	--	(3)
	Radon-222	1.0	Table F-4		(5), Table F-4
	Drift ambient	1.0	40		(4), (5)
Noninvolved	Waste package	0.04 (0.4 for 10% of workers)	0.1 millirem per hour		(7)
	Radon-222	0.4	Table F-4		(6), Table F-4
	Drift ambient	0.4	40		(4), (6)

a. External exposures include radiation from spent nuclear fuel and high-level radioactive waste packages to surface and subsurface workers, the ambient exposure to subsurface workers from naturally occurring radiation in the drift walls, and subsurface worker exposure from inhalation of radon-222.

b. Number of full-time equivalent workers by dose category for surface facility activities.

c. Sources:
- (1) Adapted from TRW (1999c, Table 6.2) for waste receipt, handling, and packaging operations. Values are based on dose rate distribution (fractions) from TRW (1999c, Table 6.2) for involved workers for dual-purpose canister scenario adjusted for fewer workers for retrieval. Forty-five percent of 29 involved workers would be in the 400-millirem-per-year category and 55 percent would be in the 100-millirem-per-year category.
- (2) Adapted from TRW (1999c, Table 6.2) for waste receipt, handling, and packaging operations. Values based on dose rate distribution (fractions) from TRW (1999c, Table 6.2) for noninvolved workers for dual-purpose canister scenario adjusted for fewer workers for retrieval. Twenty-eight percent of the 79 workers would be in the 25-millirem-per-year category and 72 percent would be in the 0-rem-per-year category.
- (3) Table F-4.
- (4) Section F.1.1.6.
- (5) Rasmussen (1998a, all).
- (6) Rasmussen (1999, all).
- (7) Rasmussen (1998b, all).

F.4.3 DETAILED RESULTS FOR THE RETRIEVAL CONTINGENCY

F.4.3.1 Construction Phase

F.4.3.1.1 *Human Health and Safety Impacts to Workers from Industrial Hazards*

The construction phase would entail only surface-facility activities. Table F-48 summarizes health and safety impacts to workers from industrial hazards during construction. There would be no radiological sources present during surface facility construction activities for retrieval and, hence, no radiological health and safety impacts to workers.

F.4.3.2 Operations Period

F.4.3.2.1 *Health and Safety Impacts to Workers from Industrial Hazards*

Chapter 4, Table 4-47, summarizes health and safety impacts to workers from industrial hazards common to the workplace for the retrieval operations period. The impacts in that table consist of two

Table F-48. Industrial hazard health and safety impacts to workers during construction.[a]

Worker group	Impacts
Involved	
Full-time equivalent work years[b]	1,130
Total recordable cases of injury and illness	69
Lost workday cases	33
Fatalities	0.03
Noninvolved	
Full-time equivalent work years	430
Total recordable cases of injury and illness	14
Lost workday cases	7
Fatalities	0.01
All workers (totals)[b]	
Full-time equivalent work years	1,560
Total recordable cases of injury and illness	83
Lost workday cases	40
Fatalities	0.05

a. Source: Impact rates from Table F-46.
b. Source: Table F-45.

components—health impacts to surface workers and health impacts to subsurface workers. Tables F-49 and F-50 list health impacts from industrial hazards during retrieval operations for surface and subsurface workers, respectively.

Table F-49. Industrial hazard health and safety impacts to surface facility workers during retrieval.[a]

Worker group	Impacts
Involved	
Full-time equivalent work years[b]	320
Total recordable cases of injury and illness	10
Lost workday cases	4
Fatalities	0.009
Noninvolved	
Full-time equivalent work years	870
Total recordable cases of injury and illness	29
Lost workday cases	14
Fatalities	0.03
All workers (totals)[c]	
Full-time equivalent work years	1,190
Total recordable cases of injury and illness	37
Lost workday cases	18
Fatalities	0.03

a. Source: Impact rates from Table F-46.
b. Source: Table F-45.
c. Totals might differ from sums due to rounding.

F.4.3.2.2 *Radiological Health and Safety Impacts to Workers*

Potential radiological health impacts to workers during the operations period of retrieval consist of the following components:

- Impacts to surface facility workers involved in handling the waste packages and placing them in concrete storage units

Table F-50. Industrial hazard health and safety impacts to subsurface facility workers during retrieval.[a]

Worker group	Impacts
Involved	
Full-time equivalent work years[b]	810
Total recordable cases of injury and illness	24
Lost workday cases	11
Fatalities	0.02
Noninvolved	
Full-time equivalent work years	180
Total recordable cases of injury and illness	6
Lost workday cases	3
Fatalities	0.01
All workers (totals)[b]	
Full-time equivalent work years	990
Total recordable cases of injury and illness	30
Lost workday cases	13
Fatalities	0.03

a. Source: Impact rates from Table F-46.
b. Source: Table F-45.
c. Totals might differ from sums due to rounding.

- Impacts to subsurface facilities workers from direct radiation emanating from the waste packages
- Impacts to subsurface workers from inhalation of radon-222 in the atmosphere of the drifts
- Impacts to subsurface workers from ambient radiation from naturally occurring radionuclides in the drift walls

Tables F-51 and F-52 list potential radiological health impacts for each of these component parts. The impacts to subsurface workers only vary slightly (less than 2 percent) with thermal load and are highest for the low thermal load. Thus, the values in Table F-52 for the low thermal load case, would produce the largest impacts.

Table F-51. Radiological health impacts to surface facility workers from waste handling during retrieval.[a]

Worker group	Impacts
Involved	
Full-time equivalent work years[b]	320
Maximally exposed individual dose (millirem)	4,400
Latent cancer fatality probability for maximally exposed individual	0.002
Collective dose (person-rem)	75
Latent cancer fatality incidence for overall worker group	0.03
Noninvolved	
Full-time equivalent work years	870
Maximally exposed individual dose (millirem)	280
Latent cancer fatality probability for maximally exposed individual	0.0001
Collective dose (person-rem)	6
Latent cancer fatality incidence for overall worker group	0.002
All workers (totals)[c]	
Full-time equivalent work years	1,190
Collective dose (person-rem)	81
Latent cancer fatality	0.03

a. Source: Exposure rate data from Table F-47.
b. Source: Table F-45.
c. Totals might differ from sums due to rounding.

Table F-52. Components of radiological health impacts to subsurface workers during retrieval for the low thermal load scenario.[a,b]

	Source of exposure			
Group	Waste packages	Ambient	Radon-222 inhalation	Total[c]
Involved				
Full-time equivalent work years[d]	840	840	840	840
Maximally exposed individual dose (millirem)	4,400	440	2,110	6,950
Latent cancer fatality probability for maximally exposed individual	0.002	0.0002	0.0008	0.003
Collective dose (person-rem)	200	33	160	390
Latent cancer fatality incidence for overall worker group	0.08	0.01	0.06	0.16
Noninvolved				
Full-time equivalent work years	180	180	180	180
Maximally exposed individual dose (millirem)	88	220	1,060	1,370
Latent cancer fatality probability for maximally exposed individual	0.00004	0.00009	0.0004	0.000 5
Collective dose (person-rem)	1	4	17	22
Latent cancer fatality incidence for overall worker group	0.0004	0.001	0.007	0.009
All workers (totals)[c]				
Full-time equivalent work years	1,010	1,010	1,010	1,010
Collective dose (person-rem)	200	37	180	420
Latent cancer fatality incidence for overall worker group	0.08	0.01	0.07	0.17

a. Source: Exposure data from Table F-47.
b. The variation in values among the thermal load scenarios was small. Therefore, only the largest values (for the low thermal load) are listed.
c. Totals might differ from sums due to rounding.
d. Source: Table F-45.

REFERENCES

DOE 1995 — DOE (U.S. Department of Energy), 1995, *YMP Erionite Control Protocol*, Office of Civilian Radioactive Waste Management, Yucca Mountain Project Office, Las Vegas, Nevada. [MOL.19950925.0124]

DOE 1998a — DOE (U.S. Department of Energy), 1998a, *Implementation Guide for use with DOE Order 440.1 Occupational Exposure Assessment,* DOE G 440.1-3, Department of Energy, Office of Worker Health and Safety, Washington, D.C. [240305]

DOE 1998b — DOE (U.S. Department of Energy), 1998b, *Air Quality Control Design Analysis*, BCAD00000-01717-0200-00008, Revision 00, Office of Civilian Radioactive Waste Management, Washington, D.C. [MOL.19980729.0044]

DOE 1999 — DOE (U.S. Department of Energy), 1999, “CAIRS Database, DOE and Contractor Injury and Illness Experience by Operation Type by Year and Quarter, 1993 through 1998,” http://tis.eh.doe.gov/cairs/cairs/dataqtr/q984a.htm, May 22, Washington, D.C. [244036]

Eckerman and Ryman 1993	Eckerman, K. F., and J. C. Ryman, 1993, *External Exposure to Radionuclides in Air, Water, and Soil, Exposure-to-Dose Coefficients for General Application, Based on the 1987 Federal Radiation Protection Guidance: Federal Guidance Report No. 12,* EPA 402-R-93-081, Office of Radiation and Indoor Air, U.S. Environmental Protection Agency, Washington D.C. [225472]
Eckerman, Wolbarst, and Richardson 1988	Eckerman, K. F., A. B. Wolbarst, and A. C. B. Richardson, 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion*, Federal Guidance Report No. 11, EPA-520/1-88-020, U.S. Environmental Protection Agency, Office of Radiation Programs, Oak Ridge National Laboratory, Oak Ridge, Tennessee. [203350]
EPA 1996	EPA (U.S. Environmental Protection Agency), 1996, *Ambient Levels and Noncancer Health Effects of Inhaled Crystalline and Amorphous Silica: Health Issue Assessment*, EPA/600/R-95/115, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C. [243562]
Gotchy 1987	Gotchy, R. L., 1987, *Potential Health and Environmental Impacts Attributable to the Nuclear and Coal Fuel Cycles,* NUREG-0332, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, Washington, D.C. [234603]
IARC 1987	IARC (International Agency for Research on Cancer), 1987, *Silica and Some Silicates*, World Health Organization, United Nations, Lyon, France. [226502]
IARC 1997	IARC (International Agency for Research on Cancer), 1997, *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Silica, Some Silicates, Coal Dust and* para-*Aramid Fibrils, Volume 68,* IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, World Health Organization, United Nations, Lyon, France. [236833]
ICRP 1977	ICRP (International Commission on Radiological Protection), 1977, *Recommendations of the International Commission on Radiological Protection,* ICRP Publication 26, Pergamon Press, Elmsford, New York. [221568]
ICRP 1991	ICRP (International Commission on Radiological Protection), 1991, *1990 Recommendations of the International Commission on Radiological Protection*, Publication 60, Volume 21, Numbers 1-3, Pergamon Press, Elmsford, New York. [235864]
ICRP 1994	ICRP (International Commission on Radiological Protection), 1994, *Protection Against Radon-222 at Home and at Work,* Publication 65, Pergamon Press, Oxford, Great Britain. [236754]
Jessen 1999	Jessen, J., 1999, “Final Closure Phase Years based on March 99 EF’s,” electronic communication to Ikenberry et al., Jason Technologies Corporation, Las Vegas, Nevada. [MOL.19990526.0030]

Kamrin 1988	Kamrin, M. A., 1988, *Toxicology – A Primer on Toxicology Principles and Applications: Indoor & Outdoor Air, Drinking Water, Food, Workplace Environment*, Lewis Publishers, Inc., Chelsea, Michigan. [243888]
Maheras and Thorne 1993	Maheras, S. J., and D. J. Thorne, 1993, *New Production Reactor Exposure Pathways at the Idaho National Engineering Laboratory,* NPR-8957, EG&G Idaho, Inc., Idaho Falls, Idaho. [243737]
McKenzie 1998	McKenzie, D., 1998, "Erionite Encounters in Expanded Layouts," electronic mail to D. Walker (Jason Technologies Corporation), December 21, Morrison Knudsen Corporation, Las Vegas, Nevada. [MOL.19990511.0294]
Mettler and Upton 1995	Mettler, F. A., Jr., and A. C. Upton, 1995, *Medical Effects of Ionizing Radiation, Second Edition,* W. B. Saunders Company, Philadelphia, Pennsylvania. [244122]
MSHA 1999	MSHA (Mine Safety and Health Administration), 1999, "Table 6. – Number of Contractor Injuries, Injury-Incidence Rates, Average Numbers of Employees, and Employee Hours, by Work Location and Mineral Industry," http://www.msha.gov.stats/wq964+06.htm, March 11, Washington, D.C. [243568]
NCRP 1987	NCRP (National Council on Radiation Protection and Measurements), 1987, *Ionizing Radiation Exposure of the Population of the United States: Recommendations of the National Council on Radiation Protection and Measurements*, Report No. 93, Bethesda, Maryland. [229033]
NCRP 1993	NCRP (National Council on Radiation Protection and Measurements), 1993, *Risk Estimates for Radiation Protection,* Report No. 115, Bethesda, Maryland. [232971]
NCRP 1996	NCRP (National Council on Radiation Protection and Measurements), 1996, *Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground, Recommendations of the National Council on Radiation Protection and Measurements,* Report No. 123, Bethesda, Maryland. [225158, Volume 1; 234986, Volume 2]
NIOSH 1996	NIOSH (National Institute for Occupational Safety and Health), 1996, "Silica, crystalline (as respirable dust), IDLH Documentation" (downloaded from http://www.cdc.gov/niosh/idlh/14808607.html, April 8, 1999), Washington, D.C. [243424]
NJDHSS 1996	NJDHSS (New Jersey Department of Health and Senior Services), 1996, "Hazardous Substance Fact Sheet – Silica, Cristobalite," Trenton, New Jersey. [243425]
Rasmussen 1998a	Rasmussen, D. G., 1998a, "Radiation exposure information," electronic communication with J. Jessen (Jason Technologies Corporation), July 22, TRW Environmental Safety Systems Inc., Las Vegas, Nevada. [MOL.19990526.0029]

Rasmussen 1998b	Rasmussen, D. G., 1998b, "Radiation exposure information," electronic communication with R. Orthen (Jason Technologies Corporation), July 29, TRW Environmental Safety Systems Inc., Las Vegas, Nevada. [MOL.19990511.0386]
Rasmussen 1999	Rasmussen, D., 1999, "Additional matrix," electronic communication with attachment to D. Walker (Jason Technologies Corporation), April 16, TRW Environmental Safety Systems Inc., Las Vegas, Nevada. [MOL.19990602.0180]
Stewart 1998	Stewart B., 1998, "YMP EIS Information Request – CAIRS Statistics for Construction and Non-Construction Activities During TBM Operations," electronic communication with attachment to J. Steinhoff (TRW Environmental Safety Systems Inc.), December 17, Las Vegas, Nevada. [MOL.19990511.0298]
Technical Resources 1994	Technical Resources, Inc., 1994, *Seventh Annual Report on Carcinogens 1994*, Rockville, Maryland. [243694]
TRW 1999a	TRW (TRW Environmental Safety Systems Inc.), 1999a, *Environmental Baseline File for Human Health*, B00000000-01717-5705-00114, Revision 01, Las Vegas, Nevada. [MOL.19990608.0035]
TRW 1999b	TRW (TRW Environmental Safety Systems Inc.), 1999b, *Engineering File – Subsurface Repository*, BCA000000-01717-5705-00005, Revision 02 with DCN1, Las Vegas, Nevada. [MOL.19990622.0202, document; MOL.19990621.0157, DCN1]
TRW 1999c	TRW (TRW Environmental Safety Systems Inc.), 1999c, *Repository Surface Design Engineering Files Report*, BCB000000-01717-5705-00009, Revision 03, Las Vegas, Nevada. [MOL.19990615.0238]